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VARIATIONS IN THE VOLUME OF SURFACE RUNOFF DURING
THE SNOWMELT PERIOD: YELLOWKNIFE,
NORTHWEST TERRITORIES

by

ARCHIE GEORGE LANDALS



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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled VARIATIONS IN THE VOLUME OF SURFACE RUNOFF DURING THE SNOWMELT PERIOD: YELLOWKNIFE, NORTHWEST TERRITORIES by ARCHIE GEORGE LANDALS in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Spring snowmelt runoff is a highly variable factor in the water balance of any region which has a seasonal snow cover. Runoff from snowmelt is nonuniform over large areas and also varies locally as a result of differences in environmental conditions. The present study is a preliminary report which outlines the major environmental factors that initiate differences in the volume of snowmelt runoff in a subarctic region. Until the present investigation, most research on variations in spring runoff during snowmelt has been related to total stream discharge (Kaitera, 1949; U.S. Army Corps of Engineers, 1960; Mackay, 1966; Sommer and Spence, 1968), or to heat balance measurements during snow decay (Connaughton, 1935; U.S. Army Corps of Engineers, 1956; Jeffrey, 1968; Pyskleywec, Devar and Bray, 1968). Little attention, however, has been given to the patterns of snowmelt before the resulting runoff enters permanent streams. In particular, little work on this topic has been applied to that portion of the Canadian Shield which is underlain by permafrost.

To investigate the environmental factors which cause variations in snowmelt and runoff in the Yellowknife area, the parameters of representative sites were analyzed and compared. Total water equivalents in the snowpack of

ten contrasting plots were sampled for correlation with later runoff. Ninety degree V-notch weirs were then installed in each location to meter the rate of discharge; runoff patterns thus obtained were compared to site factors of slope, aspect, surficial material, and vegetation cover. Observations from the Department of Transport meteorological station at Yellowknife were used to represent the macroclimate of the study area.

Microclimatic data were not collected during this investigation, but since snowmelt variations are closely related to differences in slope, aspect, and density of plant cover, microclimatic functions may also be inferred. By correlating the amount of discharge with the varying physical factors of each study location, a cause-effect relationship between runoff and site was thus arrived at.

On the basis of data collected during three field seasons, it was found that while surplus water from snowmelt is available for surface runoff in each of the ecosystems studied, weather events during the period preceding active-layer freezeback is the factor most critical to the pattern and volume of runoff during the following spring. Snowmelt discharge models established during this study may prove useful in the forecasting of runoff from contrasting physical regions within much of the Canadian subarctic.

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INTRODUCTION

STUDY LOCATION

Research for this study was carried out in Baker Creek Basin, six miles north of Yellowknife, N.W.T. Baker Creek Basin is situated on the west side of Yellowknife Bay, on the North Arm of Great Slave Lake, between $62^{\circ}28'$ and $62^{\circ}43'$ north latitude and $114^{\circ}17'$ to $114^{\circ}31'$ west longitude and is slightly more than 600 air miles north of Edmonton, Alberta (Figure 1). Baker Creek Basin is one of a series selected for study under the International Hydrologic Decade program. This program was established by a number of cooperating countries to study all aspects of water balance in small, well defined research units for the ten year period 1965 to 1974. Baker Creek Basin, an area of approximately seventy square miles, was selected by A. H. Laycock and approved by the I. H. D. National Committee for three major reasons:

- 1) it is fairly representative of much of Northern Canada;
- 2) it is readily accessible by both air and road and
- 3) it is supplied with a reasonable record of meteorological and hydrological data (Figures 2a and 2b).

Within Baker Creek Basin, two small sub-basins have been selected for more intensive study: they are Pocket Lake sub-basin with an area of thirty-five acres,

Figure 1
LOCATION OF BAKER CREEK STUDY AREA
WITHIN THE MACKENZIE RIVER DRAINAGE BASIN



Figure 2a

MAP OF STUDY AREA SHOWING EXTENT OF BAKER CREEK BASIN
AND LOCATIONS OF ASSOCIATED METEOROLOGICAL AND HYDROLOGICAL INSTRUMENTS

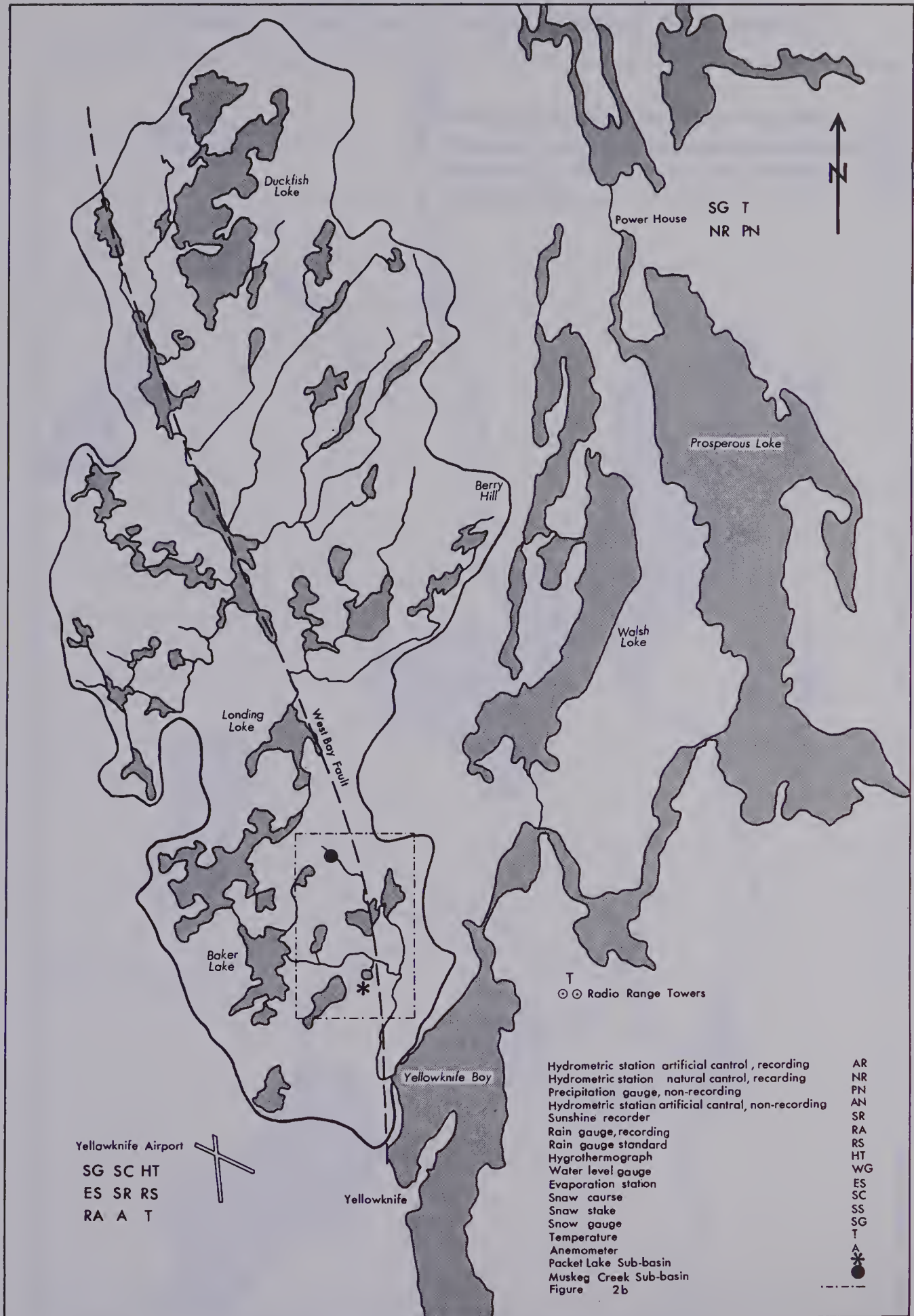
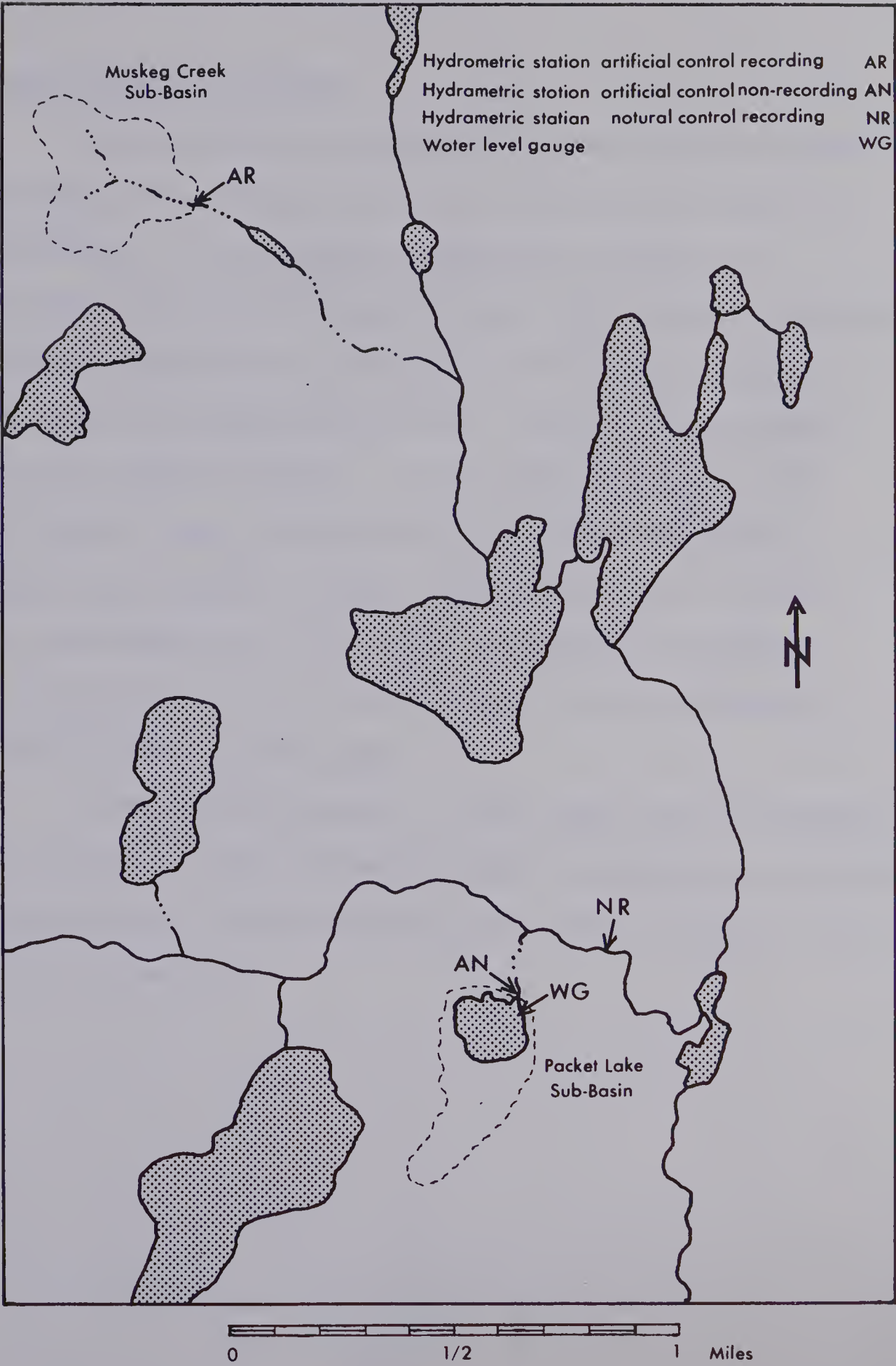


FIGURE 2b
MUSKEG CREEK AND POCKET LAKE SUB-BASINS
SHOWING LOCATIONS OF HYDROLOGICAL INSTRUMENTS



and Muskeg Creek sub-basin which is approximately fifty-five acres in size (Figure 2a).

GENERAL PURPOSE OF STUDY

Yellowknife is located in an area which receives relatively low precipitation, yet the annual runoff is considerable. The abundant runoff can largely be attributed to several major factors: the limited storage capacity of extensive outcrops of the Canadian Shield, a low rate of evapotranspiration, and the concentrated period of spring snowmelt. This study focuses on the last factor, that of the relationship between spring snowmelt and surface runoff. To analyze this relationship, representative sites were compared to determine the variations in runoff which result from differences in environmental conditions.

A secondary purpose of this study was to determine which areas of future research might be pursued to achieve a more complete understanding of the water balance in the Canadian Subarctic.

CHAPTER I

METHOD OF APPROACH

FIELD WORK

Data for this study were collected over the course of three field seasons. In 1968, research was carried out during the period April to July; the field area was again visited in October to obtain information on active-layer freezeback. The 1969 field season commenced in early April and finished at the end of May. Final investigations were completed in April, 1970.

FIELD PROCEDURE

Field research consisted of four distinct phases. The following describes the equipment used in each phase, discusses the problems encountered in the use of this equipment, and outlines the type of data collected.

1. Snow Surveys: to determine the amount of water available for spring runoff, snow surveys were carried out along transects in both Pocket Lake and Muskeg Creek sub-basins. Snow surveys were taken during the period of maximum snow accumulation immediately before the inception of the spring runoff period. Snow surveys were

carried out on April 23 and 24, 1968, on April 12 and 13, 1969, and on April 16 and 17, 1970. The snow surveys consisted of 150 point measurements taken at representative locations using a Mount Rose Snow Sampler (Plate 1). This sampler consists of a coring tube which is used to determine the depth, specific gravity, and water equivalent of snow. Water equivalents are determined by weighing the sample core of snow which gives the specific gravity when correlated with the depth of snow at a particular point.

2. Use of V-Notch Weirs: to facilitate measurement of snowmelt runoff, 90°V-notch weirs were installed at ten representative locations. The following describes the criteria used in the selection of sites, the problems encountered in the installation of weirs and the specifications for the use of 90° V-notch weirs.

A. Selection of Weir Sites - general reconnaissance was carried out in May 1968 during the critical snowmelt runoff period so that representative sites could be determined for the installation of V-notch weirs. Locating sites suitable for the measurement of snowmelt runoff was often difficult. The following criteria were used to select sites:

- (1) Runoff plots would have well-defined divides so that the area could be clearly delimited.

Plate 1. Mount Rose sampler used for the snow
surveys of the study, April 17, 1970.



- (2) Sites would possess divides of sufficient relief that ground water movement would be confined within the runoff plot.
- (3) Sites would have a single outlet so that all runoff would be intercepted by the weir.
- (4) Outlets to selected sites would be narrow enough so that dams could be readily constructed.
- (5) Gradient of the outlet stream would be sufficient to provide a large stilling pond above the gauge and adequate drainage below the weir.
- (6) Sites selected for runoff measurements would be relatively homogeneous with respect to bedrock, surficial material, vegetation cover and aspect, so that runoff differences introduced by individual environmental variables would be amenable to interpretation.
- (7) Sites were selected to cover all major snowmelt influencing factors.

It was difficult to insure that all the above conditions were present in every study plot. An example of the difficulty encountered is provided by a site in Muskeg Creek; although every attempt was made to carefully delimit the divides of this drainage site during the snowmelt period of 1968, it was later found that an error had nevertheless occurred. When computed against area, runoff amounted to slightly over seven inches of water, whereas

snow survey data indicated that only 2.75 inches of water would be available from snowmelt. This is a relatively flat-lying area and delimitation of divides proved to be inaccurate. This error may have been increased by seepage through fractures in the underlying bedrock* which are not readily apparent at the surface or by water flowing across the divides during periods of peak discharge. The result of such inaccuracies was that data from this particular site were relatively meaningless, except to suggest periods of peak flow.

B. Weir Installation - the following outlines the procedure used to install V-notch weirs so that minimum seepage and a high level of accuracy in flow measurements would be obtained.

The outlet to the site selected for gauging was first cleared to bedrock wherever possible. The main part of the dam consisted of a sheet of three-quarter inch waterproofed plywood which was cut to fit the contours of the bedrock as closely as possible. The plywood dam was then sealed to the bedrock by backfilling with a mixture of bentonite and local clay. Bentonite, a colloidal clay, swells to approximately twenty times its dry volume when wetted and thus produces a satisfactorily impervious bar-

*

This is doubtful, however, since fractures should be sealed by ice at this time of year.

rier (Rollins and Dylla, 1964, p. 268). Where space was insufficient to allow backfilling with bentonite and clay, roofing tar was used as a substitute to seal the plywood to the bedrock. This worked satisfactorily if applied when the surfaces were warm and dry but was of little value when they were wet. Both the pool above the weir and the drainage channel below were lined with rocks to reduce erosion around the gauge.

The plywood was then fitted with a 90° V-notch weir plate and a gauging stake, calibrated in hundredths of a foot, was fastened to the upstream side of the plywood to facilitate reading of the flow head through the weir.

C. Specifications for Standard 90° V-notch Weirs - the standard 90° V-notch weirs used in this study are constructed from three-sixteenth inch sheet metal with a six-inch 90° notch cut in the center of the plate. The downstream side of the V is bevelled at an angle of forty-five degrees. These plates are fastened to the downstream side of the plywood which serves as a dam across the outlet of the runoff plot. The upstream side of the plywood is bevelled at forty-five degrees to insure a smooth flow of water past the weir (Plate 2). The Department of Energy Mines and Resources, Water Survey of Canada, requires that all dimensions be correct to within plus or minus one thirty-second of an inch. This requirement was adhered to.

Plate 2. One of ten nonrecording 90° V-notch
weirs used in the collection of snow-
melt runoff data, April 29, 1969.



To insure accurate flow measurements, weirs must be installed so that a stilling pond is provided upstream, thus effectively reducing the velocity of the approaching water. Weirs must also be installed in such a manner that flow is able to break completely free on the downstream side of the weir plate. The Water Measurement Manual published by the U.S. Department of the Interior, Bureau of Reclamation (1953) suggests ten conditions necessary for accurate flow measurements with Standard 90° V-notch weirs. These provisions are drawn up for the measurement of flow in irrigation channels and are impossible to meet in all cases under the much different conditions prevailing in Baker Creek basin. Wherever possible, however, these provisions were met, thus it is felt that a high degree of accuracy was maintained during all flow measurements.

3. Collection of Snowmelt Runoff Data: snowmelt runoff data from the ten instrumented sites were collected during the spring of 1969. Weir measurements were taken manually, and due to the distance between gauges and the time required to walk from site to site, readings were not made on as regular a basis as desired. This problem was largely overcome, however, by taking readings as often as possible (eight times daily during the critical snowmelt period) which was sufficient to establish diurnal patterns of the

rise and fall of snowmelt runoff. In addition to the irregularity of readings, a number of other problems were encountered in the collection of snowmelt runoff data. Obstruction of weirs, stilling ponds, and drainage channels by freezing was a significant problem. Although it was impossible to keep these locations free of ice at all times, this difficulty was reduced by removing the ice at each visit. Since most gauges are non-recording and only spot readings are taken, the accuracy of measurement is not affected if a short period of time is allowed (after ice removal) for flow patterns to be re-established.

Where recording devices are used, such as the main gauges on Muskeg Creek and Baker Creek (Figure 2b), freezing is a major problem and results in measurements which may be completely erroneous. The natural control for the recording gauge on Baker Creek is completely blocked by icing* for most of the snowmelt runoff period (Plate 3). Meaningful streamflow records are unobtainable under such conditions. Either the gauge must be relocated or some means must be devised to keep the control

* In early winter, stream flow is impeded by freezing in the form of anchor ice at the bottom and floating ice at the surface, while shallow channel sections may freeze solidly. Water still flowing from upstream floods over the frozen surface of the channel as the flow becomes increasingly impeded. Alternate flooding and freezing, continuing most of the winter, may build up layers of ice six feet in thickness.

Plate 3. Blockage of the natural control for Baker Creek recording gauge by icing prohibits accurate streamflow measurements during the critical snowmelt runoff period. The top of the well which houses the recorder is approximately seven feet above normal stream level. In the photograph only one foot of the well casing protrudes above the ice. April 12, 1969.



free of ice if records are to be obtained at this time of year.

Disruption of the gauges by ice expansion which caused leaks around the dams was a problem in some cases. Where this occurred, leaks were repaired with bentonite or tar. For future research using similar sites, it would be of value to investigate other types of material for bonding the plywood to the bedrock.

4. Active Layer Measurements: the thickness of the active layer was measured with a metal probe at a number of points in 1968 and again in 1969. Fifty random measurements were made on October 22nd, 1968 in Muskeg Creek sub-basin. On October 26th, 1969 measurements were taken at ten foot intervals along four transects in Pocket Lake sub-basin and along four transects in Muskeg Creek sub-basin; ninety active layer depths were thus recorded. Measurements were made in late fall when the active layer had attained a maximum thickness so that a reasonable estimate of the total potential volume available for moisture storage in areas of organic terrain could be arrived at.

LABORATORY PROCEDURE

Two separate phases of the research for this study were carried out in the laboratory. The first of these was the analysis of a number of soil samples to determine

moisture content. The second was the compilation and conversion of data so that they could be utilized on a comparative basis.

1. Soil Moisture Determinations: twenty samples of frozen peat were collected from under the snow cover in Pocket Lake and Muskeg Creek sub-basins on April 12 and 13, 1969. Samples were transported in air-tight plastic bags to insure that no moisture loss occurred. These samples were analyzed in the laboratory to determine water content as well as available storage space for moisture uptake in the spring. Samples were first weighed in their original condition then air dried and reweighed, the difference being the water content. Samples were then completely saturated and weighed a third time. The relationship of the weight of the original sample to the weight of the saturated sample indicates the approximate degree of saturation at the time of freezing* and permits a reasonable estimate of the amount of moisture which might be absorbed by the peat in the spring.

2. Data Conversion: snowmelt runoff data collected in the field are in the form of hundredths of a foot of head

* Little addition of water to the peat is possible after it has become frozen, although it appears that a small amount of moisture may be added by sublimation from the suprajacent snow, analagous to the Bergeron process in the atmosphere (see Ashwell, 1968, p. 47).

through 90° V-notch weirs. These readings cannot be used on a comparative basis and must be converted to cubic feet per second (cfs). This is accomplished by means of the cone formula which has been empirically derived for standard 90° V-notch weirs.* This data is easily converted to cubic feet per minute or cubic feet per hour by making the appropriate multiplications. For the purpose of this study, most data are expressed in cubic feet per hour due to the small volumes of flow involved. Once data are converted to a useable form, they are plotted on hydrographs on an hourly basis. Daily curves are then plotted to obtain total flow volumes on a diurnal basis. Once flow volumes are calculated they are totaled to obtain the volume of discharge for the entire runoff period. Discharge volumes in cubic feet are then converted to inches of runoff for each site on both a daily and total runoff-period basis. This conversion to inches of runoff allows direct comparison between sites by removing the variations in volume caused by differences in area. Patterns obtained by comparing these data are discussed in detail in Chapters four and five.

* Cone formula: $Q = 2.49H^{2.48}$

Where Q = discharge

H = head on weir in feet

Water Measurement Manual, U.S. Department of the Interior, Bureau of Reclamation, 1953, p. 187.

CHAPTER II

PHYSICAL SETTING

Since variations in snowmelt runoff in any area are controlled by differences in environmental conditions, it is necessary to have a general understanding of the physical setting of the area before commencing a study of these variations. The following chapter is a brief description of the geology, surficial material, weathering processes, vegetation, soils, and climate of the research area and a summary of the ways in which they affect runoff patterns.

BEDROCK GEOLOGY

Baker Creek Basin is situated within the Canadian Shield as opposed to most of the Mackenzie River drainage system which flows over bedrock of sedimentary origin. The complex geologic history of the Yellowknife area has resulted in the outcropping of a number of contrasting rock types. These distinctive lithologies, because of differences in weathering patterns, differences in porosity, and differences in albedo result in variations in runoff patterns. Summarizing Campbell (1947) the Archean geologic sequence for the Yellowknife area consists of:

1. extensive outpouring of volcanic flows
2. intermittent vulcanism and sedimentation
3. sedimentation with little vulcanism
4. granitic intrusions accompanied by thrust faulting
5. intrusion of diabase dykes
6. major strike slip faults

These geologic events are of major significance with relation to the present day topography of the area. The West Bay Fault which divides Baker Creek Basin roughly in half from northwest to southeast has been studied in detail by the use of diamond drilling by the Consolidated Mining and Smelting Company. Campbell (1947) suggests that the west side has moved slightly more than 1,000 feet downward and 16,000 feet south relative to the east side. Movement along this fault which is located immediately east of both Pocket Lake and Muskeg Creek sub-basins has resulted in bringing the Yellowknife sediments and volcanics (greenstones) into close association with the granitic intrusives to the west. Muskeg Creek and Pocket Lake sub-basins, however, lie entirely within the granitic portion of the Baker Creek basin and therefore variations in runoff due to lithologic differences were not intensively studied. Differences in runoff due to lithology should be considered for future research in the Basin.

Movement along the West Bay Fault has resulted in a definite lineation of lakes in the Basin and to a large

extent controls the drainage pattern of Baker Creek. From the northern end of the Basin southward to Landing Lake, the course of Baker Creek itself is strongly controlled by the West Bay Fault. Tributaries generally flow southwest toward the fault and in many cases are controlled by small cross faults, dykes and veins. These features are less resistant than the country rock and weather to form narrow steep-sided valleys.

Bedrock, modified by weathering and erosion is largely responsible for the physiographic differences of the area. Local relief seldom exceeds 200 feet and Berry Hill, standing some 370 feet above the level of Great Slave Lake (or 880 feet above sea level), is the highest point in the Basin. Granitic areas have a somewhat different physiography than the greenstone areas. This is summarized by Jolliffe (1945), who suggests that areas underlain by granitic rocks show the least local relief and commonly stand at a higher elevation than areas underlain by rocks of the Yellowknife group.

SURFICIAL DEPOSITS

Although bedrock strongly controls the topography of the area, runoff is influenced to a marked degree by the unconsolidated material overlying the bedrock. Most of the surficial deposits in the area are materials deposited directly by glacial ice or by glaciofluvial action.

In many glaciated areas, the landscape consists almost totally of features produced by glacial erosion or deposition. In the Yellowknife area, however, this does not appear to be the case and Bird (1955) suggests that the major landforms already existed by the early Pleistocene and in most areas were developed during the Tertiary. Although the major features existed by the Pleistocene they were definitely modified by glaciation. The primary result of glaciation was the reduction of local relief. Glacial erosion scoured and rounded the upland areas while deposition filled the adjacent depressions. Glacial erosion of the upland areas of the study basin produced such features as roche moutonees, chattermarks, crescentic gouges and striations, all of which indicate an ice movement direction from east-northeast. Glacial erosion also produced numerous hollows of various size which act as temporary reservoirs to reduce runoffs and increase evaporation.

On a microscale, the results of glaciation are much more complex, and have a marked influence on local runoff patterns. As previously noted, glacial ice resulted in scour of upland areas and deposition of adjoining depressions. Deposition in low-lying areas was also facilitated by the action of glacial meltwater. Glacio-fluvial processes were active in a number of ways and produced deposits of distinctively different types. The

initial action of glacial melt water was the sloughing off of loose material from the uplands to carry it to adjoining depressions. This resulted in deposition of poorly-sorted material in many of the depressions while leaving expanses of the upland areas bare. Associated with these deposits is glacial outwash which has been reworked to some degree to produce poorly sorted and stratified gravels.

Another main category of glacial melt water deposits are those associated with proglacial lakes. These materials are of two main types - fine lacustrine sediments and beach sands and gravels. The more extensive of these deposits can be interpreted as products of Glacial Lake McConnell which Craig (1965) identified as extending from Great Bear Lake through Great Slave Lake to Lake Athabasca. This extensive proglacial lake was formed immediately after deglaciation some 7,000 years B.P. as a result of differential isostatic depression.* Beach deposits associated with Glacial Lake McConnell are locally very prominent; Joliffe (1945) identified these in the Baker Creek Basin up to elevations of 240 feet above

*The general direction of drainage in the Yellowknife area was away from the ice to the northwest. As the ice retreated eastward, this drainage pattern was disrupted by the greater isostatic rebound in the west away from the margin of the stagnating ice thus resulting in extensive ponding of meltwater.

the present level of Great Slave Lake (about 735 feet above sea level). These beach deposits consist of well-sorted sand and fine gravel, they are generally well drained, and provide optimal locations for vegetation growth.

Glacio lacustrine deposits are also important locally but are not as extensive as the beach materials. Lacustrine deposits consist of very fine impervious clays and usually underlie the muskegs in Baker Creek Basin. In areas of non-permafrost impervious clay often seals fractures, cracks and shatter zones below depressions, thus preventing groundwater flow and allowing optimal muskeg development.

Glacial meltwater deposits have a marked effect on runoff patterns from various areas. Different depositional materials have variable percolation rates, different storage capacities, characteristic permafrost patterns and support distinctive ecosystems.

Glacial deposits of many types have resulted in the blockage of previously existing drainage channels. This blocking of channels, coupled with glacial erosion and the low local relief of the area has resulted in the formation of a deranged drainage pattern and is partially responsible for the numerous lakes and muskegs of the area.

POST-PLEISTOCENE WEATHERING AND EROSION

The time span of 7,000 years since the retreat

of glacial ice from the Yellowknife area has been insufficient to allow great modification of the landscape by weathering and subaerial erosion. A number of distinguishable features which are important to runoff patterns have nevertheless resulted.

The two main rock types in Baker Creek Basin vary in their susceptibility to weathering and erosion. Local relief indicates that the greenstones are more easily eroded than the granites. In terms of glacial erosion this appears to have been the case. The more abundant and better preserved striations on the greenstones, however, indicate that post-glacially they have eroded to a lesser extent than the granites. Physical weathering affects the granites and the greenstones similarly, but chemical weathering is more prevalent on the granites. This observation contrasts with that made by Ritchie (1956, p. 539) in northern Manitoba. He suggests that there is a greater amount of soil on the greenstone ridges than on the granite since the former rock weathers somewhat more rapidly than the latter. Climatic and lithologic differences in northern Manitoba possibly cause more rapid weathering since soils developed insitu by the breakdown of local bedrock in the Yellowknife area are virtually non-existent.

Chemical Weathering

Although chemical weathering in the Yellowknife

region is relatively slow due to the cold climate, it is still significant. The granites of the study area are affected by two chemical weathering processes, spheroidal weathering and granular disintegration. Greenstones, however, are not affected to a great extent. Spheroidal weathering in the study area results from hydration of the feldspars in granite and is a minor process which produces small slabs that seldom exceed one-half inch in thickness. Granular disintegration on the other hand is a much more important process and is active everywhere on exposed granite. Chemical decay results in separation of the individual minerals of the surface layer of the granite; these angular fragments of crystal grain size (grus), assisted by freeze-thaw action and running water, are carried downslope where they collect in depressions. This process leaves the surface of the granite pitted and thus able to hold a film of water on the surface thereby increasing evaporation and decreasing runoff. Since deglaciation less than one-half inch of the granite surface has been removed by granular disintegration as evidenced by comparing granite exposures with adjacent glacially polished, striated dikes. The greenstones have not been affected by chemical weathering to an appreciable extent as indicated by the excellent preservation of abundant striations and chatter marks (Plate 4). The greenstones, because of their smoother surfaces,

Plate 4. Striations and chattermarks on the green-stones near Baker Creek gauge. Ice movement was from east-northeast or from right to left in photograph. April 16, 1970.



produce runoff with a smaller amount of precipitation than the granites.

Physical Weathering

Physical weathering in the study area is active on both the granites and greenstones but except for scattered occurrences, has not affected the general form of ice-scoured features. Important physical weathering processes are joint block separation, exfoliation, and, especially, frost shattering. In some areas, notably on steep slopes, frost shattering has resulted in the surface being almost entirely mantled with angular fragments. They are variable in size from very small to several feet in diameter. The shattered rock surfaces are slowly being colonized by vegetation (especially crustose lichens and scattered jackpines) and will eventually introduce considerable variation in local runoff patterns.

VEGETATION

As in any location which is colonized by a non-uniform vegetation cover, ecosystems of the study area are a useful indicator of variable water balance patterns. Vegetation to a large extent is controlled by, and to a lesser extent controls, moisture balance characteristics. A number of distinctive vegetation types are closely related to abrupt environmental variations and are easily recognized. The following description of these sites

and their characteristic vegetation types is accompanied by a brief summary of their major water balance variations.

For simplification, plant communities are divided into two major categories - those occupying the upland ridges and those colonizing the major valleys of the study area (referred to as depressional sites). Within the upland category are six distinct ecosystems; depressions are occupied by four separable plant types.

Upland Ridge Sites

1. Jackpine-lichen ecosystem: the most noticeable features of the upland ridges are the large expanses of bare rock. These areas are essentially devoid of soil and plant cover except for scattered pockets that support a minimal amount of vegetation. The prevailing plants here are jackpine (Pinus banksiana) and many species of crustose lichens (Plate 5). Jackpine here are very infrequent and generally exhibit a stunted growth form. Average height is approximately twelve feet, diameter at breast height (dbh) is approximately three inches and crown cover is generally less than five per cent.* These trees and occasional juniper (Juniperus communis and J. horizontalis) and paper birch (Betula papyrifera) are rooted in fractures and small depressions filled with mineral soil and thin

*In this study, percentages are written in full when values are approximate while exact measurement are given as numerals.

Plate 5. Sparse jackpine-lichen ecosystem occupying granite exposure. The roche moutonee with the smooth stoss slope and plucked lee slope is further evidence of ice advance from the east-northeast (right to left in photograph). May 20, 1969.



layers of organic material. Crustose lichens are abundant and widespread as a pioneer species on bare rock. Such exposed outcrops are characteristically moisture-deficient due to wind-removal of snow in winter and rapid runoff of snowmelt and rainfall in spring and summer. Although the total volume of runoff is limited due to the reduced snow on these sites, retention is very low thus a surplus may result. Scattered within the jackpine-lichen ecosystem are moisture-retaining depressions in which some organic soil has accumulated. These sites are primarily colonized by sedges (Carex spp. and Eriophorum spp.) and mosses (primarily Sphagnum spp.).

2. Jackpine-bearberry ecosystem: the second vegetation type which occupies the upland areas colonizes those sites covered by thin drift. This material is generally coarse and stony, and has a low moisture-holding capacity. The species which characterize this plant community are jackpine and bearberry (Arctostaphylos uva-ursi). Trees generally exhibit poor growth and seldom exceed a height of fifteen feet or a dbh of four inches. Crown cover in this ecosystem averages approximately twenty-five per cent. Ground cover is generally continuous and is greatly dominated by bearberry (Plate 6). Lichen (especially Cladonia rangiferina) is locally very abundant. Due to the sparsity of arboreal vegetation, some snow is annually removed by wind and sublimation from these upland areas.

Plate 6. Jackpine-bearberry ecosystem. Charred log in the left foreground is evidence of a past forest fire. Note the varying rates of snowmelt resulting from differences in exposure. May 5, 1969.



There is, however, sufficient snow retention to provide considerable spring runoff, especially because of the low storage capacity of the surficial material.

In several locations, extensive deposits of coarse, well drained beach ridge material occur, which provide the best site conditions for plant growth in the area. Although two distinctively different plant communities occur (one an aspen-birch ecosystem and the other a community dominated by pure stands of jackpine), water balance patterns are uniform over most of the beach ridges. These sites experience only limited snow redistribution, and spring snowmelt is retarded as a result of the dense stands of trees. Due to the slow spring melt and the high infiltration capacity of the porous beach material, runoff is limited from these areas.

3. Aspen-birch ecosystem: two tree species combine here to dominate this association, aspen (Populus tremuloides) and birch (Betula papyrifera) (Plate 7). Together they create a sixty per cent crown cover, are twelve to fifteen feet in height, and have an average dbh of two to three inches. Understory vegetation consists primarily of alder (Alnus crispa) and wild rose (Rosa spp.) with a ground cover of various species of grasses, mosses and lichens.

4. Jackpine ecosystem: this vegetation type also occurs on beach ridge material. Jackpine here forms nearly pure stands which have a very sparse understory (Plate 8).

Plate 7. Birch-poplar ecosystem colonizing one of the beach ridges. July 16, 1968.

Plate 8. Jackpine ecosystem on one of the beach ridges in the Yellowknife area. Clearing in the foreground is a result of highway construction. May 20, 1969.



Stands are composed of trees fifteen to twenty feet high which normally form closed canopies. Stem diameter averages four inches. The apparent reason for two different plant communities occupying one uniform site is that jackpine is a fire-induced species and this ecosystem may be a subsere induced by fire.*

5. White spruce ecosystem: scattered throughout the upland areas are gentle slopes mantled by accumulations of mineral and organic soils. These sites are occupied by white spruce (Picea glauca). Trees are often vigorous and in the more protected sites, stands up to forty feet tall and six inches dbh are common (Plate 9). Crown cover is generally in excess of seventy-five per cent. Alder is the major shrub in this ecosystem and the thick ground cover is made up of a variety of mosses and lichens. Drifting results in the accumulation of snow along the peripheries of this community which provides a moisture surplus in the spring. Snowmelt is slow due to the shading of the tree canopy but considerable runoff occurs because of limited storage capacity.

6. Black spruce ecosystem: where large depressions have formed in upland areas their floors are often sealed by

* Jackpine is a pyro-edaphic species which colonizes sites after fire. Fire removes ground vegetation and humus, providing soil conditions conducive to the growth of this tree. Jackpine cones are serotinous and fire is instrumental in opening them, thus allowing seed dispersal (Smithers, 1962).

Plate 9. White spruce community near Baker Creek gauge. Poor growth of the trees can be attributed to arsenic pollution from the nearby gold mines. April 10, 1970.



fine lacustrine clay. This material impedes drainage, resulting in a plant community dominated by black spruce (Picea mariana). Ritchie (1959) found similar occurrences of black spruce in northern Manitoba and suggests that local dominance of this species is correlated with the existence of deposits of heavy clay. Poor drainage of these depressions also results in the presence of organic soil. This material is largely built up by such organic-accumulating species as labrador tea (Ledum groenlandicum) and sphagnum mosses (Sphagnum spp.). Growing conditions are poor in these sites and trees seldom exceed fifteen feet in height and three inches dbh. Crown cover is variable; occasional stands approach eighty per cent cover over small areas, but the average is more often fifty per cent.

Drifting results in accumulation of snow in such depressions and provides a moisture surplus in the spring, but because of poor drainage these sites produce only minor amounts of runoff. Snowmelt completely saturates the organic material and often results in standing water at the surface. Most of this water is lost through evaporation and transpiration although some seepage eventually contributes to runoff. Drying out of these sites in summer lowers soil moisture content thus a somewhat more mesophytic ground vegetation than is normally associated with black spruce is in evidence.

Depressional Sites

Low-lying valleys having soils which remain saturated for most of the year have a much more uniform environment than do upland areas. Depressions are relatively flat, drainage is impeded or non-existent, and nearly everywhere the surface is mantled by a thick accumulation of organic soil. Except for those sections of depressions which are protected by adjacent ridges, exposure is similar in depressions. Vegetation is an able indicator of site conditions in these locations and has a great influence on the water balance. The following ecosystems are present in depressional sites:

1. Black spruce-labrador tea ecosystem: the most heavily vegetated depressional sites are the black spruce muskegs (Plate 10). This plant association is greatly dominated by two species black spruce and labrador tea. A thick ground cover of sphagnum is everywhere present. Although crown cover is often in excess of seventy-five per cent, trees seldom reach a height of fifteen feet and a dbh of three inches. This ecosystem is separable from the black spruce communities of upland ridge sites by a difference in water balance patterns. Whereas the latter may occasionally suffer from a diminished water supply because of their exposed position, the former location receives runoff throughout the growing season. Furthermore, the valleys

Plate 10. Typical black spruce-labrador tea ecosystem which occupies extensive tracts of muskeg in the Yellowknife area. Note the compaction of snow on April 17, 1970.



receive considerably more snow from wind redistribution than the less extensive black spruce communities of the upland depressions. Water balance patterns for the black spruce-labrador tea sites are thus characterized by heavy snow accumulations in the winter and retarded melt in the spring due to protection by the dense tree canopy and often steep valley walls. Permafrost which contains a large percentage of ground ice is usually present at a shallow depth in these locations due to the well-known insulating effect of the thick sphagnum layer and extensive shading by vegetation.

2. Willow-ground birch ecosystem: a second muskeg ecosystem is dominated by willow (Salix spp.) and ground birch (Betula pumila var. glandulifera) (Plate 11). Alder is abundant around the drier margins. Ground cover consists primarily of sphagnum mosses, sedges, and aquatic grasses. Willows exhibit a stunted growth and seldom exceed four feet; ground birch averages two feet in height. (The retarded growth-form suggests browsing by moose although the terminal stems show no evidence of this.) Water balance patterns here are similar to those of the black spruce muskegs in that they both receive heavy snow accumulations in the winter. Spring melt, however, is more rapid in the willow-ground birch ecosystem. Although shrubs provide nearly continuous cover in this association, their deciduous nature results in reduced shading during

Plate 11. Willow-ground birch ecosystem along Baker Creek. Tape indicates the depth of icing present in the location on April 23, 1968. Date of photograph is July 16, 1968.



the critical spring snowmelt period. Where permafrost is present under this ecosystem the active layer develops more rapidly than in the black spruce-labrador tea association. This too is a consequence of the deciduous character of the dominant species but it is further aided by a normally thin moss layer. Where permafrost is not present, the seasonally frozen ground thaws rapidly for the same reasons.

3. Labrador tea ecosystem: the third distinctive bog ecosystem which occurs in depressional areas is dominated by labrador tea. Sphagnum, cloudberry (Rubus chamaemorus) and horsetail (Equisetum spp.) are locally very abundant. Ground cover is nearly continuous but seldom exceeds one foot in height. As a result snow accumulation is less here than in the two previously discussed associations. Although this ecosystem occupies a depressional site, snow may be removed by wind and sublimation because of the lack of protection by an overstory of vegetation. (Drifting from surrounding ridges offsets the loss of snow around the margins of these areas, but this input of snow does not balance the total amount removed.) Spring melt and runoff is rapid from these sites due to exposure to wind and radiation.

4. Sedge meadow ecosystem: the final ecosystem delimited for this study is the sedge meadow, dominated by species

of Carex and Eriophorum. Scattered ground birch is the only other major plant. This association has a water balance similar to the labrador tea ecosystem but accumulates more surface water in the spring. By late summer, however, these sites have undergone sufficient desiccation to become considerably drier than the labrador tea ecosystem. They experience seasonally contrasting moisture regimes for the following reasons: sedge meadows occupy drainage sites, thus receive large inputs or runoff in the spring. Permafrost is largely absent here, thus once the seasonally frozen ground thaws, interior drainage aids normal evapotranspiration to rapidly dry the upper soil horizon.

Man's Influence on Vegetation

The activities of man have drastically affected the vegetation in portions of the Baker Creek Basin, especially near Giant Yellowknife Mine. In addition to the damage commonly caused by cutting, the vegetation adjacent to Giant Mine has been greatly modified by fire. Fires were employed in the early period of mineral exploration to facilitate easier study of rock outcrops. An organic mantle which took thousands of years to develop was purposely sacrificed by some prospectors to save a few hours labour. These fires, although set some decades ago, still influence the runoff regime of the southern portion of Baker Creek Basin. Release of water in the spring is more

rapid here because of the greatly reduced organic layer and vegetation cover.

Air pollution has also played a role in destroying vegetation in the area surrounding Giant Mine. Arsenic, derived from arsenopyrite in the refining of gold ore was formerly released unchecked into the atmosphere. This had a devastating effect on much of the vegetation (Plate 12) and wildlife in the area surrounding the mine. Measures are now being taken to reduce this pollutant and vegetation appears to be recovering somewhat.

The main result of man's interference with vegetation in the Baker Creek Basin has been a general denudation of the biotic landscape which has altered natural water balance patterns; snow removal is more pronounced from upland areas, spring snowmelt is accelerated, and runoff from man-altered locations is more rapid. Additional research is needed to quantify man-induced modification of runoff patterns in the Baker Creek Basin. Information gained here could benefit areas in the North which are beginning to experience similar intensive utilization by man.

Effects of Icing on Vegetation and Water Balance

Massive accumulations of ice (icings) build up over long sections of the valley adjacent to Baker Creek during the winter months (Plate 13). This buildup occurs downstream from local constrictions where the ice freezes

Plate 12. Arsenic pollution has disrupted the natural vegetation in the southern portion of Baker Creek Basin. April 16, 1970.

Plate 13. Because of icing, massive accumulations of ice occur along extensive portions of the valley adjacent to Baker Creek. May 14, 1968.



to the bottom thus blocking normal channel flow. Hydrostatic head at these locations forces water to the surface where it soon freezes. Measurements taken in April 1968 and again in April 1969 indicate a depth of icing in excess of six feet for much of the valley.

Icing has a pronounced effect upon vegetation. Areas which are seasonally covered by icing are dominated by willow and ground birch while adjacent unaffected areas are dominated by black spruce and jackpine (Plate 14), although in many parts of the valley, drainage and soil characteristics are such that black spruce would normally be the dominant vegetation. A reasonably accurate map of the distribution of icing patterns along Baker Creek could be obtained by plotting the extent of this icing-controlled topo-climatic climax from aerial photographs.

Icing is also significant in terms of local water balance patterns in that it acts as a reservoir for retention storage. Runoff is reduced throughout the winter period as it accumulates in the form of ice. Water, stored in this manner, is released in the spring, thereby substantially increasing runoff for this period. Few quantitative measurements have been made and little is known of the exact effects of icing on vegetation, geomorphology or water balance. This is an interesting topic worthy of consideration for future research in the basin.

Plate 14. Icing controls the distribution of the willow-ground birch ecosystem along much of the Baker Creek Valley. Areas covered by icing are dominated by willow and ground birch while unaffected areas are normally colonized by jackpine and spruce. May 5, 1969.



SOILS

The five factors generally considered important in the formation of soils are climate, geology, relief, organisms and time. Although all these functions are undoubtedly important to the formation of soils in the Yellowknife area, the two which appear to have had the greatest influence are climate and time.

Glacial ice which was responsible for the removal of pre-existing soil from the Yellowknife area, retreated approximately 7,000 years B.P. This short period coupled with a cold climate has been insufficient to allow the formation of mature zonal soils. Nevertheless, all three soil orders, zonal, azonal, and intrazonal, are represented in the Yellowknife region. Azonal soils consist of newly exposed areas of till and freshly decomposed bedrock. Deep organic accumulations, formed in muskegs and bogs under conditions of poor drainage, are typical intrazonal soils. Zonal soils, formed in response to climate and vegetation on well-drained sites, are represented in the Yellowknife area by poorly developed podzols. These podzols have the following characteristic profile horizons, although poorly developed:

A₀ - very thin, leaf mold and acid humus

A₁ - thin acid layer, rich in humus, generally
yellowish to reddish brown in color

- A₂ - leached, eluviated horizon from which iron oxides and colloidal humus have been removed, characteristically light in color
- B - illuvial horizon or zone of accumulation of colloids and iron oxides, generally brown in color
- C - unaffected parent material - generally thin glacial till, outwash, or beach ridge material

Soil development or lack of development plays an important role in moisture balance patterns. Soils influence rates of infiltration, percolation rates, water retention capacity and plant moisture relationships. Soils in the Yellowknife area are important in terms of runoff in two contrasting ways. The thick accumulations of organic soils in bogs and muskegs are very important because of their great moisture storage capacity, while the general lack of soil development on bare rock and unconsolidated material results in minimal storage and facilitates rapid runoff.

CLIMATE

An understanding of climate is essential to any water balance study. Snowmelt runoff patterns are dependent upon climate since it is responsible for the amount of water in the snowpack and controls the rate of release of this water in the spring. The following discussion

of some of the more important climatic elements sets the stage for the analysis of snowmelt runoff patterns in Chapter five.

Temperature and Insolation

Latitude is the major factor controlling temperature in the Yellowknife area. Yellowknife at 62° 30' north has very short summers and long winters. At the time of the winter solstice Yellowknife receives slightly less than five hours of insolation. Conversely, the summer solstice results in about twenty hours of insolation. Besides the duration of sunshine, incoming solar radiation is affected in two other ways by the north south migration of the sun. The lower angle of incidence in the summer increases the intensity of solar radiation. It also decreases the length of the path of the sun's rays through the atmosphere thus resulting in less absorption and scattering by the air.

Continentality also plays a major role in controlling temperature. Yellowknife is situated approximately 750 miles from the Pacific Ocean, about 650 miles west of Hudson Bay and some 350 miles from the nearest part of the Arctic Ocean. The great distance from the Pacific is further accentuated by the Rocky Mountains which impede the flow of maritime Pacific air masses toward the interior of the continent. Areas such as those around Yellowknife, far removed from the moderating influence of large water

bodies, have far greater contrasts of temperature than do coastal areas.

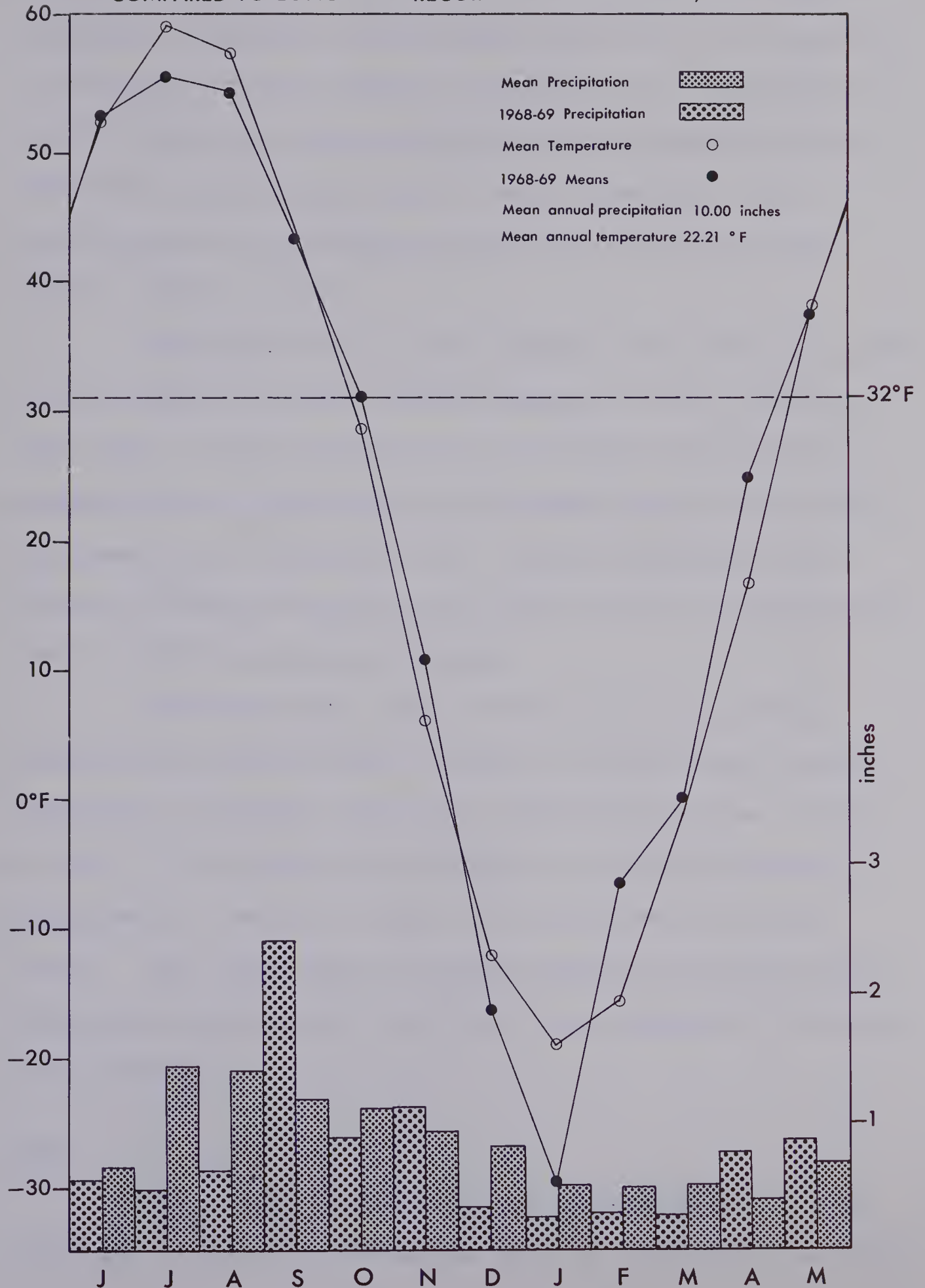
Mean monthly temperatures for the twenty-five year period from 1942 to 1967 show a large annual temperature difference. The coldest month is January, with a mean temperature of -18.9°F and the warmest month is July with an average of 60.9°F , i.e., a range of nearly 80°F . Temperature and precipitation for the year June 1968 through May 1969 is compared with mean monthly temperatures and precipitation in Figure 3.

Precipitation

Precipitation in the form of rain and snow provides the amount of water available for evaporation, transpiration, runoff and storage increase and is therefore fundamental to water balance evaluations.

Yellowknife is located in an area of low average annual precipitation. Mean annual precipitation as calculated from the Monthly Record for the Yellowknife Airport is 10.0 inches. The low precipitation is due to three main factors. First, precipitation is low because of the prevalence of cold air masses over the area. Cold air has little moisture-holding capacity and is able to produce only limited precipitation. Secondly, there are few precipitation mechanisms to induce release of what little water vapor does occur in the air. There are no orographic barriers capable of causing significant uplift

Figure 3
 MONTHLY TEMPERATURE and PRECIPITATION
 DURING STUDY PERIOD (JUNE 1968 – JUNE 1969)
 COMPARED TO LONG TERM RECORDS AT YELLOWKNIFE, N.W.T.



of air masses. Convectional and cyclonic mechanisms rarely occur in winter and are at best poorly developed in summer. Finally, as mentioned previously, Yellowknife is isolated from the sources of marine air. Although the Pacific Ocean is a long distance from Yellowknife and is separated from the area by the Rocky Mountains, most precipitation is nevertheless derived from this source (Kakela, 1969, p. 47).

Precipitation is quite evenly distributed throughout the year but with a slight maximum in late summer and early fall. This is due to the increased frequency of precipitation mechanisms, the increased water vapor holding capacity of the warmer air, and the greater availability of moisture from water bodies which are completely free of ice at this time of year.

Precipitation, which occurs during the seven winter months from October to April when the mean monthly temperature is below freezing, accumulates on the surface as snow. The accumulation of snow is rapidly released in spring which results in very wet conditions and rapid runoff. The variations in spring snowmelt resulting from differing environmental conditions are examined in Chapters four and five.

Wind

Wind, like temperature and precipitation, is an important climatic variable and must be considered in water

balance studies. The direction, velocity, and duration of wind influences snow redistribution as well as the rate of evaporation and transpiration.

The twelve monthly and one annual mean duration-intensity wind roses measured at the Yellowknife airport for the ten year period 1957 to 1966 are shown in Figure 4 (after Kakela, 1969, p. 51). these wind roses, the direction of the wind is represented by the orientation of the lines. The hourly duration of wind from any one direction multiplied by the mean speed of the wind from that direction yields a duration intensity value for the wind blown from that direction in miles per hour. The lengths of the lines on the wind roses are proportional to these duration-intensity values.

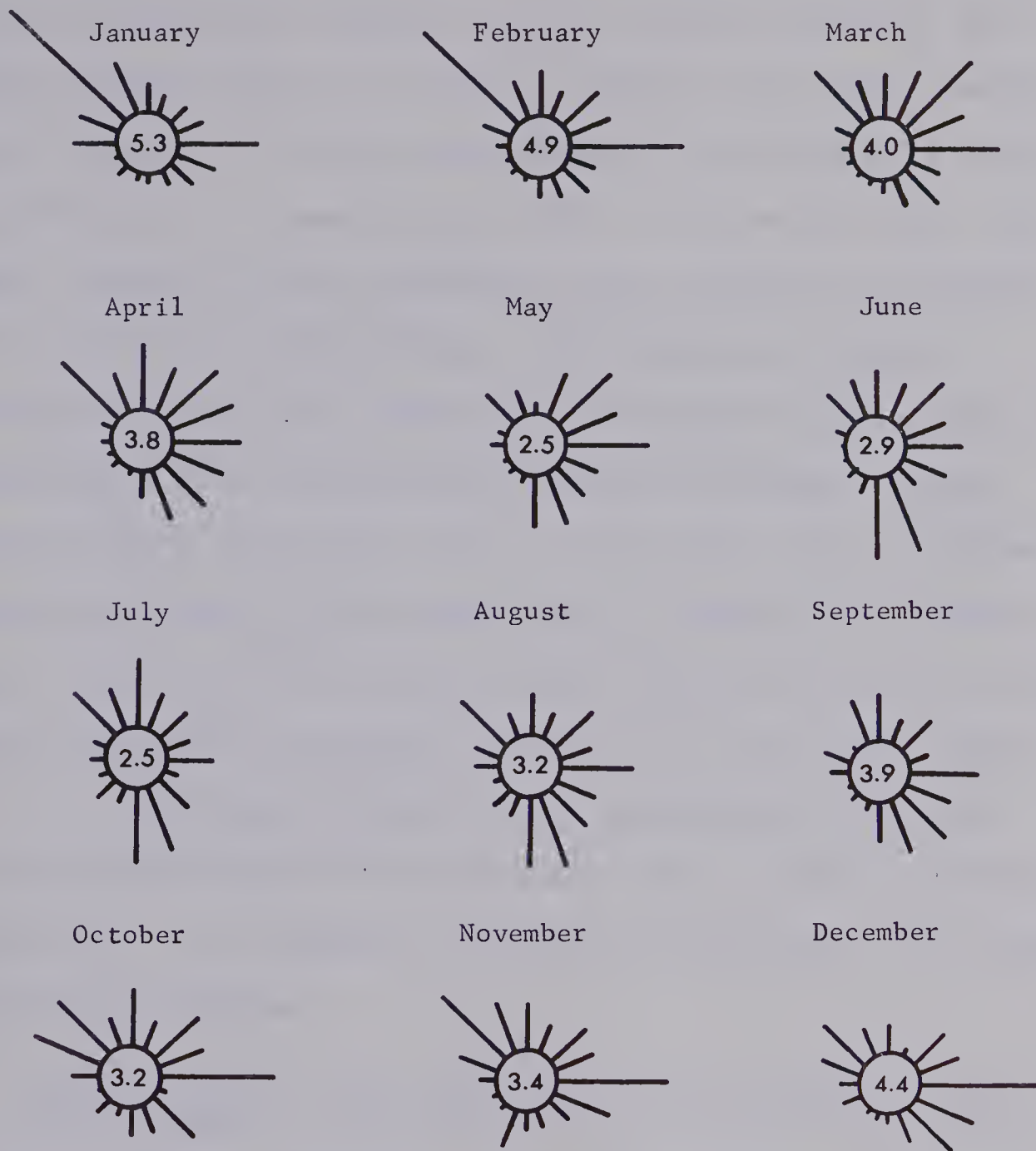
In winter, the dominant wind direction is from the east with secondary patterns from the northeast and northwest. In summer, the patterns are more variable, but show a preferred orientation from the south.

PERMAFROST

Yellowknife, as located on Map 1246A, Permafrost In Canada, lies within the zone of discontinuous but widespread permafrost. Perennial frozen ground or permafrost as defined by Brown (1969, p. 13) is "the thermal condition under which earth materials exist at a temperature below 32°F continuously for a number of years."

Figure 4

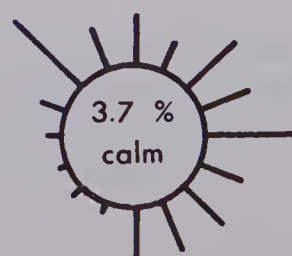
MEAN DURATION-INTENSITY WIND ROSES FOR YELLOWKNIFE AIRPORT, 1957-66



RELATIVE DURATION-INTENSITY, BY MONTH



ANNUAL



After Kakela, 1969

Permafrost has a number of important effects upon water balance patterns. Groundwater that enters a zone of permafrost (which is not already saturated) becomes immobilized as ice and is removed from the dynamic water balance. If the unconsolidated material is already saturated (as is usually the case in the study area) the upper surface of the permafrost zone provides an impermeable barrier to infiltration. This barrier impedes drainage in much the same manner as bedrock and is partially responsible for the extensive tracts of muskeg. Since approximately sixty per cent of the study area is exposed bedrock and most of the remainder is underlain by permafrost* or bedrock at shallow depth (usually less than three feet) groundwater movement occurs on a local scale only.

The upper surface of the permafrost zone also restricts the depth of rooting of trees in many locations (Plate 15). In seasons of moisture deficiency this reduces evapotranspiration.

a. Active Layer: the layer above the permafrost which thaws in the summer and refreezes in the winter is known

* Bateman (1949) states that in the Yellowknife area, permafrost occurs wherever surficial deposits exceed a depth of six feet; he found that it does not occur beneath bedrock which is not protected by a blanket of insulating till or peat.

Plate 15. Permafrost restricts rooting to a shallow depth as illustrated by this wind-thrown black spruce. This site is mantled by a deep organic layer that maintains permafrost close to the surface. May 20, 1969.



as the active layer (Embleton and King, 1968). Water balance patterns in the Yellowknife area are strongly influenced by the active layer. It acts as a reservoir for retention storage, taking up large volumes of water in some seasons and releasing it later. The degree of saturation of the active layer in the spring has a marked influence on snowmelt runoff patterns as this controls the available storage space for moisture uptake. These and other relationships of the active layer to snowmelt runoff patterns are discussed in detail in subsequent sections of this study.

NON-PERMAFROST AREAS

Scattered throughout Baker Creek Basin are small areas which are not underlain by permafrost. They also act as reservoirs for retention storage. Since the upper layer of these areas freeze seasonally, they influence snowmelt runoff patterns like the active layer. The degree of saturation at the time of freezup is again critical to runoff patterns of the following spring.

CHAPTER III

SPRING SNOWMELT

This chapter discusses the variables involved in the melting of the snowpack and analyzes the relationships between snowmelt concentrations and streamflow patterns in the Yellowknife area.

MELTING OF THE SNOWPACK

The melting of snow depends on the interactions of a number of heat transfer processes and upon the condition of the snowpack. The U.S. Army Corps of Engineers (1956, p. 14) lists the sources of heat for snowmelt as:

1. absorbed solar radiation
2. net long-wave radiation exchange between the snowpack and its environment
3. convective heat transfer (sensible heat) from the air
4. latent heat of vaporization released by condensation
5. conduction of heat from underlying ground
6. heat content of rainwater

How each of these heat-transfer mechanisms affects snowmelt in the study area is examined in the following sections.

1. Absorbed solar radiation

The amount of solar radiation absorbed by the snowpack is the difference between the quantity received

and the quantity reflected by the pack (albedo). The amount of solar radiation received at any one point is a function of latitude, elevation, angle and direction of slope, cloud cover, vegetation cover, and the time of day and year.

The latitude of the study area ($62^{\circ} 30'N$) and the corresponding high angle of incidence greatly influences the amount of incident solar radiation. The low solar altitude even during the snowmelt period (approximately 40° at noon) results in a considerable reduction in potential energy per unit area. The great angle of incidence lengthens the path of the sun's rays through the atmosphere and results in greater scatter, atmospheric absorption and reflection. The latitudinal reduction in solar intensity is partially compensated by the increased number of hours of daily sunshine (approximately fifteen during the snowmelt period which normally extends from late April to the middle of May).

Direction and degree of slope also effect the amount of incident solar radiation. South-facing slopes have the longest possible duration of sunlight, with the steeper slopes receiving more solar radiation due to the lower angle of incidence.

Vegetation and cloud cover are other important variables which modify local radiation budgets. The amount of reduction is determined by the density and type of plant cover. Dense stands of spruce and pine provide

complete shadowing in parts of the study area while leafless deciduous trees intercept far less solar radiation during the period of snowmelt.

Cloud cover also reflects and absorbs large and variable amounts of short-wave radiation. Water vapor is the most important absorbing constituent of the atmosphere and Blair and Fite (1965, p. 69) suggest that clouds of ordinary thickness and density may reflect as much as seventy-five to eighty per cent of the incident radiation, although part of this may be re-reflected to earth from higher clouds. Cloud cover also scatters much of the incoming solar radiation. The resultant diffuse sky radiation is largely independent of direction and on days of dense cloud cover it tends to even out the differences in incoming solar radiation which result from aspect (Geiger, 1966, p. 375). On a clear day a south slope may receive three times as much direct sunlight as a north aspect while on an overcast day the two aspects receive approximately equal amounts of radiation (Reifsnyder and Lull, 1965, p. 23).

The relative amount of solar radiation reflected by the snowpack is known as albedo. The U.S. Army Corps of Engineers (1960, p. 5) suggests that albedo ranges from more than eighty per cent for new-fallen snow to as little as forty per cent for melting, late-season snow. Wendland (1967) found a drop in albedo at Yellowknife from

about seventy per cent to twenty per cent over a two-week period in April coincident with the darkening of the ablation surface and the loss of continuous snow cover. Wendland's monitoring of the net-radiation balance at Yellowknife during April, 1966 coincide well with the duration and intensity of snowmelt as empirically observed during the present study.

2. Net Long-wave Radiation Exchange

Some of the radiation reflected by the snowpack is back-radiated by the atmosphere or forest cover. Under conditions of clear skies heat loss from the snowpack is generally greater than heat gain from back radiation. Cloudy skies or forest canopies may result in back radiation being greater or less than the loss from the snowpack, depending upon the ambient air temperature. Under low clouds or under a forest canopy the downward long-wave re-radiation is a function of the temperature of the undersurface of the radiating body. For clouds under one thousand feet and for the undersurface of the forest canopy this temperature can be considered equal to the free air temperature (U.S. Army Corps of Engineers, 1956).

As described in Chapter four the greatest portion of runoff occurred during the period April 29 to May 4.

Examination of cloud cover on these days* and on April 28 (the date of major snowpack ripening) indicates the significance of long-wave radiation to snowmelt in the Yellowknife area. Clear skies prevailed during four per cent of this period while cloud cover was scattered sixty-three per cent, broken twenty-seven per cent, and overcast six per cent of the time. This degree of cloud cover results in significant long-wave re-radiation and tends to modify the difference in rate of melt caused by aspect. It also reduces outgoing radiation at night and prevents temperatures from dropping as low as on clear nights (Donn, 1965, p. 20).

3. Convective Heat Transfer

Convective heat transfer from the air is of relatively minor importance compared to net radiation in transmitting energy to the snowpack. Heat and water vapor are transferred to or from the snow cover by turbulent mixing, dependent upon the temperature gradient of the air above it. A downward temperature or vapor-pressure gradient results in a transfer of energy to the snowpack, while an upward gradient reduces the energy available to melt or sublimate the snow.

* Cloud cover data are recorded at the Yellowknife airport on an hourly basis as clear (no clouds), scattered (1/10-5/10 of the sky covered) broken (6/10-9/10), or overcast (10/10).

4. Latent Heat of Vaporization

Transfer of water vapor to the snowpack results in the release of its latent heat as the moisture condenses. On snow surfaces this heat is of considerable hydrologic significance since for each gram of water condensed, approximately seven grams of ice can be melted. This is due to the great difference between the latent heat of vaporization of water and the latent heat of fusion of ice (Garstka et al 1958, p. 93). This source of heat becomes increasingly important with the disappearance of continuous snow cover as the melt season progresses. Areas of exposed soil (Plate 23) or standing water (Plate 22) supply water vapor to the air. This vapor may subsequently condense upon the snow surface and release its latent heat.

5. Heat from Underlying Ground

The conduction of heat upward to the snowpack from the underlying ground (geothermal heat) is very low and can be regarded as negligible. Since much of the study area is underlain by permafrost, most of the geothermal heat is dissipated before reaching the base of the snow cover.

6. Heat Content of Rainwater

Heat is transferred to the snowpack by rain as it is cooled to the temperature of the snow. For every degree

centigrade that one gram of water cools, it supplies one gram calorie of heat to the snow. This amount of heat is relatively minor considering normal rainfall temperature (the U.S. Army Corps of Engineers [1956, p. 180] suggests that one inch of rainfall at a temperature of 46°F produces only 0.1 inch of melt water). Since no significant rainfall occurred during the 1969 snowmelt period in Baker Creek Basin, this source of heat can be dismissed.

CONDITION OF THE SNOWPACK

The amount of snowmelt resulting from a given quantity of heat to the snowpack is dependent upon the thermal quality of the snow. The U.S. Army Corps of Engineers (1956, p. 143) defines thermal quality as "the ratio of heat necessary to produce a given amount of water from snow to the amount of heat required to produce the same quantity of melt from pure ice at 32°F." During the melt season, snow is usually isothermal at 32°F and contains an amount of free water. Melting of the ice matrix releases this free water and results in a total volume of water greater than that produced from melting the ice crystals alone.

The change that occurs in the snowpack from the time that accumulation begins until runoff occurs is known as ripening or metamorphism (U.S. Army Corps of Engineers, 1956, p. 143). The several physical processes contributing

to the ripening of snow are: 1) heat exchange at the surface by radiation, convection and condensation; 2) percolation of melt or rainwater into the snowpack; 3) internal pressure due to weight of the snow; 4) wind; 5) temperature and water vapor differences within the snowpack; and 6) heat exchange at the ground surface. As soon as the liquid water content of the snowpack is equal to the liquid-water-holding capacity of the snow, it is said to be ripe and runoff begins to occur.

APPLICABILITY OF SNOWMELT THEORIES TO THE PRESENT STUDY

Although numerous equations have been developed for calculating snowmelt under various conditions these are of little value to the present study. Most snowmelt equations are used for flood forecasting; they deal with relatively large areas and are mainly concerned with the timing of peak flow. To apply snowmelt theory to the present study it would be necessary to have a greater amount of micro-meteorological data as well as an accurate measurement of the area covered by snow at any particular time during the snowmelt period.

An understanding of the energy sources involved in snowmelt is of definite value to the present study. Although the preceding sections have discussed the sources of heat for snowmelt as separate entities, they are in fact interdependent and closely related to such environmental

conditions as vegetation, slope, aspect, snowfree areas and open water.

The following section discusses these interrelations and although many of the meteorological variables upon which they depend are not given, they are reflected by the environmental conditions which cause variations in the pattern of snowmelt.

Heating of the air by solar radiation is relatively minor; of greater consequence is the heating that results from the passage of air over terrain which is heated by solar radiation. This supplies heat to the air by convective transfer and long-wave radiation, as the air is much less transparent to this radiative component than to solar or short-wave radiation. Bare ground, water and forested areas serve as energy-exchange surfaces to convert radiant energy into sensible heat. Water and ground surfaces that contain water provide moisture to the air by evaporation as they are heated. This water vapor may subsequently condense upon a snow surface to release its latent heat.

The amount of heat and moisture which may be advected into or out of a region depends upon the nature of the plant cover and the areal extent of the snow cover. There is little advective energy transfer over large homogeneous regions; advection of heat is much more important to snowmelt in heterogeneous areas. For example consid-

erable heat and moisture may be carried to a site which is situated to the lee of a snow-free area or a body of open water.

The air in forested regions warms faster than the air over barren snowfields due to the lower albedo of a vegetated surface. This enables the advective transfer of heat from forested to barren site. Considering snowmelt rates in forested areas and forest openings, the U.S. Army Corps of Engineers (1956, p. 185) suggests that rates of melting are considerably greater in large clearings than they are in forests. While these areas have approximately the same air temperatures and vapor pressures as do the forested sites (due to large-scale mixing of the air) the higher wind speeds encountered over the snow in the open result in greater melts by convection and condensation. Melting due to absorbed solar radiation is considerably greater in the open than it is in the forested areas, and this coupled with the larger convection-condensation melt component, results in a greater melt in open sites.

By contrast, in small forest openings, shading and shielding by adjacent trees results in less solar radiation and a diminished convection-condensation melt, with the result that the rate of melting is slower. This factor coupled with the normally greater accumulation of snow in small forest openings, often results in these

sites retaining snow patches which do not melt until late spring.

In conclusion, melt rates are fastest in large forest openings, of intermediate duration in the forests themselves, and slowest in small openings. However, very large barren areas with no surrounding forest cover can be expected to have the slowest snowmelt, since few exchange mechanisms are present to convert radiant energy to sensible heat and moisture.

RELATIONSHIP OF SNOWMELT CONCENTRATIONS TO STREAMFLOW IN THE YELLOWKNIFE AREA

Mean annual precipitation recorded from 1942 to 1969 at the Yellowknife airport is ten inches. Snow surveys within Baker Creek Basin from 1967 through 1969 indicate that approximately three inches or one third of the total annual precipitation is accumulated in the snow-pack. This concentration of moisture is rapidly released as the snow melts during the latter part of April and early May. Concentration of one third of the year's precipitation into such a short period results in rapid runoff which normally makes up a large proportion of the annual streamflow. In most snow-covered regions, this produces a period of peak stream discharge coincident with the period of release.

In the Yellowknife area, however, this is not always the case. Sommer and Spence (1968) examined the

annual flow regime of the Yellowknife River and found that peak discharge occurred in July rather than coinciding with the period of snowmelt in late April. They also determined that the flow regime of this river is not appreciably affected by summer precipitation. They state, however, that there is a close correlation between the rise and fall of summer temperatures and the rise and fall of the summer flow regime. The explanation they suggest for the July flow peak is related to the annual thermal regime of the active layer. Active layer temperatures during the snowmelt season are below freezing and Sommer and Spence (1968, p. 63) postulate that the active layer at this time is relatively dry because of a water deficiency in the late summer and fall of the preceding year, thus it is receptive to moisture. They suggest that melt water passes into the ground, is refrozen, and slowly released with the rise of summer temperature which results in a July maximum streamflow.

This suggested pattern of moisture uptake and release by the active layer is contrary to the findings of the present study. Results of field research from April 1968 to April 1970 indicates that during this period the active layer was always near saturation at the time of freeze-up and had only a limited capacity to absorb spring snowmelt. Since the active layer does not appear to exert a strong control on streamflow regime

some other explanation must be given for the July discharge peak. It is estimated that at least sixty-five per cent of the area of the Yellowknife River Drainage Basin is covered by standing water in the form of lakes, sloughs, and muskeg (estimation is based on Department of Mines and Technical Surveys 1:250,000 Topographic Maps). It is suggested that detention of snowmelt runoff in these numerous reservoirs is primarily responsible for the late peak in stream discharge.

Irrespective of which line of reasoning is followed in explaining the July peak in streamflow, snowmelt is nevertheless indirectly responsible for providing a large percentage of the water. It is thus clear that snowmelt runoff is a very important part of the annual water balance in the Yellowknife area.

CHAPTER IV

RUNOFF PATTERNS IN THE STUDY AREA

Environmental conditions such as aspect, vegetation cover and surficial material are distinctly related to variations in the pattern of spring snowmelt runoff. To analyze these relationships, snowmelt runoff from ten representative sites was measured during the spring of 1969 as described in Chapter one. The following chapter describes in detail eight of these sites and analyzes the runoff data obtained from them. Discussion of two sites is omitted because the data from them are questionable. Error in data is attributed to the inability to intercept all flow as well as the poorly delimited divides which made it impossible to correctly measure the area of the sub-basin.

The locations of the instrumented sites from which snowmelt runoff data were collected are shown in Figures 5 and 6. The general terrain of these two sub-basins is depicted by portions of aerial photographs in Figures 7 and 8.

Figure 5
 MAP OF POCKET LAKE SUB-BASIN
 SHOWING LOCATIONS OF MELT RUNOFF PLOTS AND V-NOTCH WEIRS



Figure 6
 MAP OF MUSKEG CREEK SUB-BASIN
 SHOWING LOCATIONS OF MELT RUNOFF PLOTS AND V-NOTCH WEIRS



Figure 7
POCKET LAKE SUB-BASIN

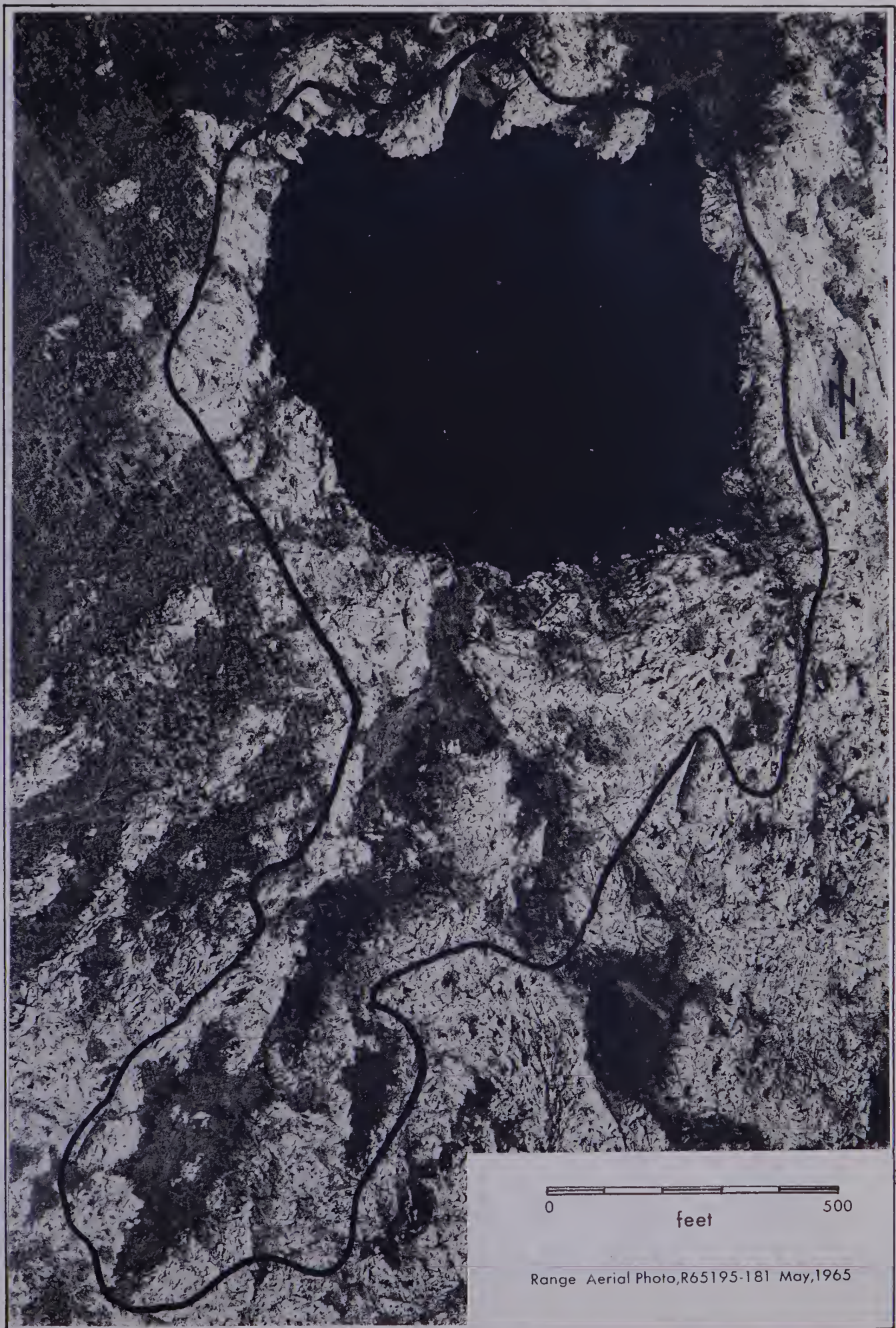


Figure 8

MUSKEG CREEK SUB-BASIN



CHARACTERISTICS OF SAMPLE PLOTS

Bare Rock Sites

Sites 1 and 2 are small areas of bare rock which have opposing aspect. These plots are similar and share a number of common characteristics. Both consist of glacially-scoured granitic bedrock, contain no unconsolidated material and are completely unvegetated. Both sites have a number of joints and fractures. These are of minor extent, and although they result in some moisture loss, no significant seepage occurs from them because the fractures are sealed by ice during the period of runoff. A number of glacially-plucked depressions occur in both sites and this, along with the inherent surface roughness of the granite (caused by granular disintegration), results in some water loss through surface retention.

Site 1 (Plate 16) is south-facing and has an area of approximately 500 square feet while the north facing plot (site 2; Plate 17), has an area of 800 square feet.

These bare rock localities are representative of large tracts of upland, except that crustose lichens are not as abundant here as they are in many similar areas. The plucked depressions also contain somewhat less organic material than is found in upland sites. The vegetation which is present consists of moss and sedges and an occasional stunted black spruce.

Plate 16. Site 1 - the south-facing bare rock plot in Pocket Lake sub-basin. Note weir in foreground. April 27, 1969.

Plate 17. Site 2 the north-facing bare rock slope in Pocket Lake sub-basin. Note concentrations of compacted snow in depression. April 16, 1970.



Vegetated Ridge Sites

Sites 3 (Plate 18) and 4 (Plate 19) were selected as being representative of the vegetated ridges. Site 3 has an area of 8,500 square feet while site 4 is 35,000 square feet in size. They also have contrasting aspect - site 3 faces north and site 4 faces south. These plots are characteristic of well-drained upland ridges mantled by a thin layer of coarse unconsolidated material which seldom exceeds one foot in depth; often it is entirely lacking. Twenty to thirty per cent of the area of these sites is bare rock. Both plots contain pockets of deeper surficial deposits which consist of a greater percentage of fine material. These depressions support the most vigorous plant communities of the sites and are generally made up of stands of jackpine. Trees in these stands are often up to fifteen feet high, four inches dbh and provide up to eighty per cent crown cover. Elsewhere, vegetation is less successful with jackpine covering approximately ten per cent of the surface. In areas of exposed bedrock, vegetation is lacking. Where present, ground cover consists of bearberry and crustose lichens, but these have a minimum effect upon snowmelt runoff because of their low growth form. Humus accumulation in these sites is minor and occurs only in the more heavily vegetated locations. It is composed of partially-decomposed pine needles that seldom exceed an inch in thickness.

Plate 18. Site 3 - north-facing vegetated plot in Pocket Lake sub-basin. V-notched weir is located twenty-five feet off left edge of photograph. April 16, 1970.

Plate 19. Site 4 - south-facing vegetated slope in Muskeg Creek sub-basin. V-notch weir is located immediately in front of figures (top of dam is visible as a thin line at snow level). April 17, 1970.



The vegetated ridge plots are representative of most sites which are covered by jackpine, although some variability in runoff occurs depending upon the amount of unconsolidated material present. In some instances, the north-facing slopes of ridges support communities dominated by white spruce. This species is indicative of more moist soil conditions which results from a lower rate of evapotranspiration on north-facing slopes. Such slopes, however, have snowmelt runoff patterns similar to the instrumented sites.

Muskeg Sites

Snowmelt data were also collected from two muskeg areas. Site 5 (Plate 20) in Pocket Lake sub-basin has an area of 167,500 square feet and site 6 (Plate 21) in Muskeg Creek sub-basin has an area of 290,000 square feet. These plots are similar in that they both contain deep accumulations of organic material overlying permanently frozen ground at a depth of two feet. Vegetation is markedly different at each site however, Site 5 is unvegetated except for a few small shrubs around the periphery. The surface of the muskeg is bare and black, and devoid of any cover. This lack of vegetation is likely due to arsenic pollution or burning.

Site 6 on the other hand has a diverse plant cover. Labrador tea is the dominant species and provides

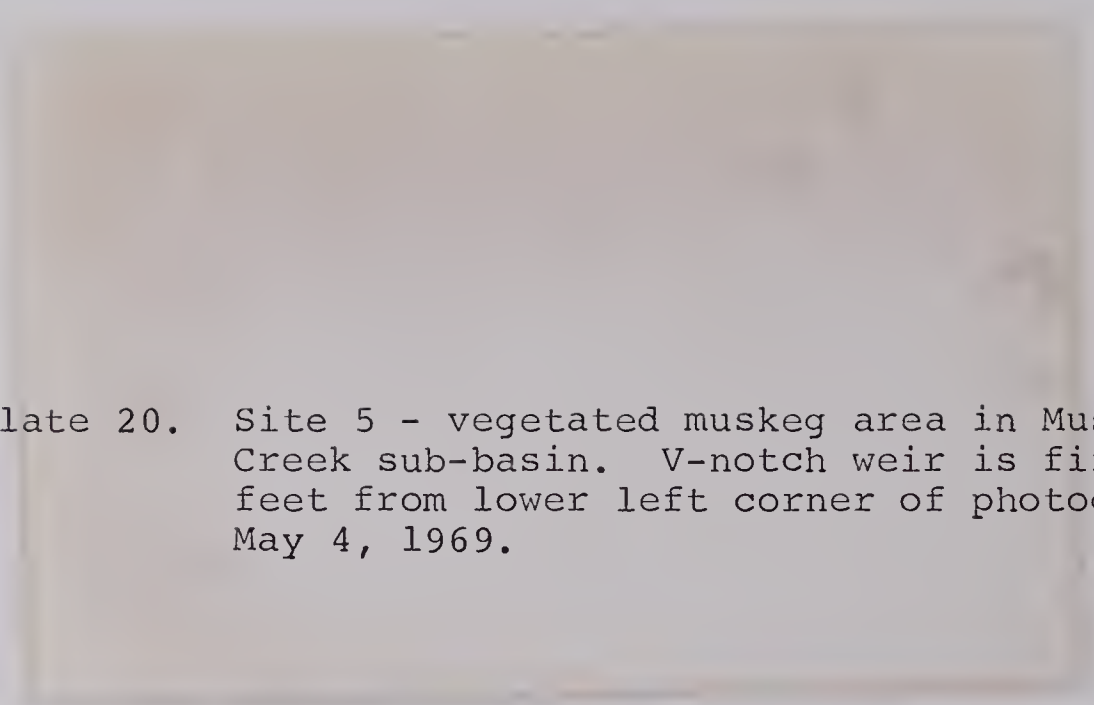


Plate 20. Site 5 - vegetated muskeg area in Muskeg Creek sub-basin. V-notch weir is fifty feet from lower left corner of photograph. May 4, 1969.

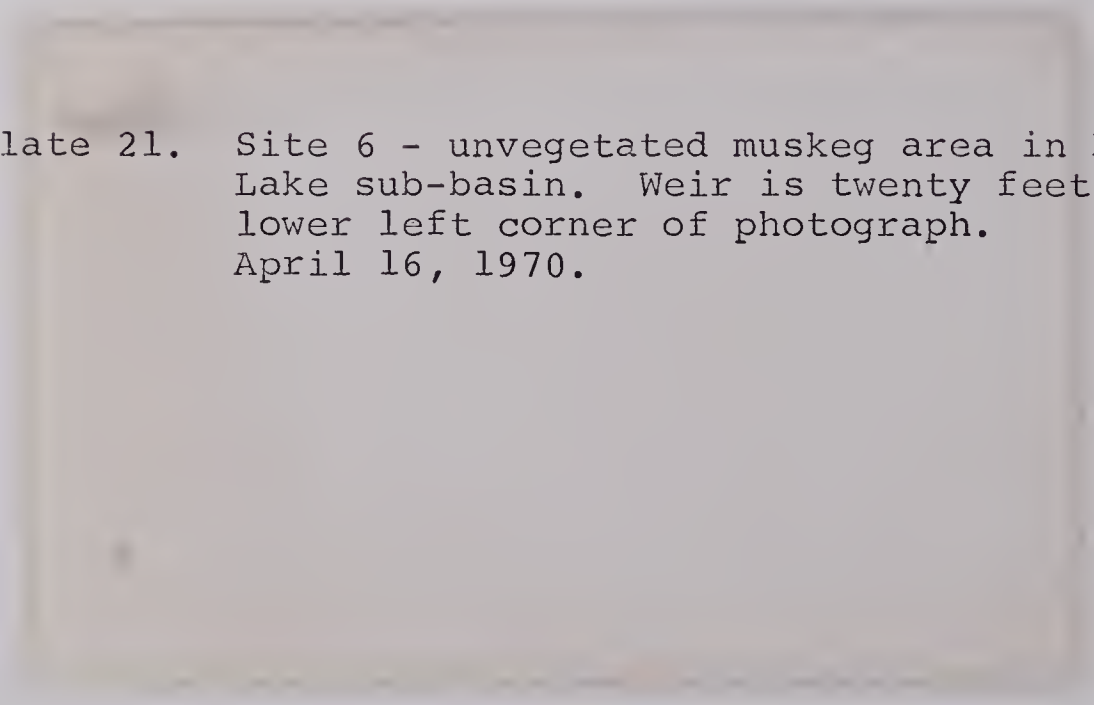


Plate 21. Site 6 - unvegetated muskeg area in Pocket Lake sub-basin. Weir is twenty feet from lower left corner of photograph. April 16, 1970.



about a sixty per cent ground cover. Associated with the labrador tea are cloudberry and scattered lichen. Black spruce and larch (Larix laricina) are the sole tree species. They range in height up to twelve feet and occur as scattered individuals or dense clumps and cover a total of about ten per cent of the area.

These two sites are representative of the large tracts of muskeg which occur throughout the Yellowknife area. Comparison of the two sites allows an evaluation of the significance of plant cover to snowmelt runoff from muskeg areas. The relationship of vegetation to the development of the active layer and its implications to water balance patterns are examined in Chapter five.

Compound Sites

Site 7 (Plate 22) is a compound* plot of 87,500 square feet consisting of a small muskeg with steeply sloping rock sides. Approximately half of the site consists of muskeg which has up to two feet of organic material overlying sand and gravel of unknown depth. One quarter of the area is steeply sloping bedrock with no vegetation cover. The remainder of the plot is covered with coarse surficial material of varying depth.

* The term compound is used in the study to refer to sites which contain more than one major type of surficial material and are colonized by several plant communities.

Plate 22. Site 7 - compound site in Pocket Lake sub-basin; note large volume of ponded surface water which does not pass through weir (located several feet off photograph toward observer). Sites such as this which contain standing water early in the melt season (and are not dry until mid-June) provide water vapor to the air. This vapor may condense upon snow surfaces and release its latent heat. May 4, 1969.



This site is poorly drained and retains a large amount of water on the surface. It is partially lost to evapotranspiration and slow release below the weir by ground water movement as the active layer develops later in the summer.

Areas of thin surficial deposits are vegetated by sparse stands of jackpine while areas of thicker drift support communities of aspen and birch. Trees in this community are small, seldom exceeding twelve feet in height and two inches dbh but constitute a dense stand in excess of eighty per cent crown cover when in foliage.

Site 8 (Plate 23) is another compound area. This is the largest plot instrumented under the present study with an area of 525,000 square feet. Muskeg forms the major ground cover of the plot and varies from the un-vegetated location described in site 5 to several areas covered by dense stands of black spruce. The divides of the site are rock slopes marked by numerous small plucked depressions upon which grow scattered jackpine. Part of the area is covered by drift of varying thickness which supports a plant cover of black spruce, white spruce, birch, willow and alder.

Site 8 gives a useful indication of how runoff from a heterogeneous area varies in comparison to the more homogeneous sites previously described.

Plate 23. Site 8 - compound site in Pocket Lake sub-basin. Weir is located fifty feet behind photographer. Patches of exposed-moist soil provide water vapor to the air which may condense on snow surfaces and release its latent heat. April 16, 1970.



The above-described sites are representative of most of the distinctive terrain and vegetation types in the Yellowknife area with one exception: no localities covered by deep accumulations of beach-ridge sands and gravels were instrumented, since no significant amount of this material occurs in Pocket Lake or Muskeg Creek sub-basins. Such deposits would undoubtedly produce yet another distinctive type of runoff.

DESCRIPTION OF RUNOFF PATTERNS

The remainder of this chapter describes flow patterns which are based on snowmelt runoff data collected in the spring of 1969. This description is subdivided into two sections: the first examines runoff patterns for the entire snowmelt period while the second section considers daily variations in discharge. Reasons for variations in runoff are discussed in Chapter five.

Runoff Patterns During the Full Snowmelt Period

The following description compares the amount of runoff occurring from each site with the volume of water present in the snowpacks calculated from snow survey data. The dates of flow commencement and termination (or duration of runoff) and the time of peak discharge are also examined.

Site 1

This south-facing bare rock location produced the least amount of runoff of all the areas studied. The snowpack on this plot contained the equivalent of 1.8 inches of water on April 12, but it resulted in only 0.04 inch of runoff. Only slightly more than 2 per cent of the snowpack was thus measured as discharge. This small amount of flow occurred early in the snowmelt period and lasted only two days (April 22 and 23; see Table 1). Although runoff ceased on April 23 the site was not completely devoid of snow until May 2.

Site 2

The north-facing bare rock site by comparison produced the greatest percentage of runoff. The snowpack contained 3.1 inches of water, of which 2.55 inches or 82 per cent was released as runoff. Flow was rapid from this plot; the beginning of runoff and peak discharge both occurred on April 29 (Figure 9). Peak discharge here was the greatest of all instrumented sites, with 1.11 inches of flow being recorded on April 29 (Table 1). Runoff on this date accounted for 43.7 per cent of the flow from the plot. Flow duration was short, lasting until May 4, a period of only six days.

Site 3

Runoff from this north-facing plot totalled 2.15

Figure 9
SNOWMELT HYDROGRAPHS OF REPRESENTATIVE SITES
SHOWING DATE OF PEAK DISCHARGE AND DURATION OF FLOW

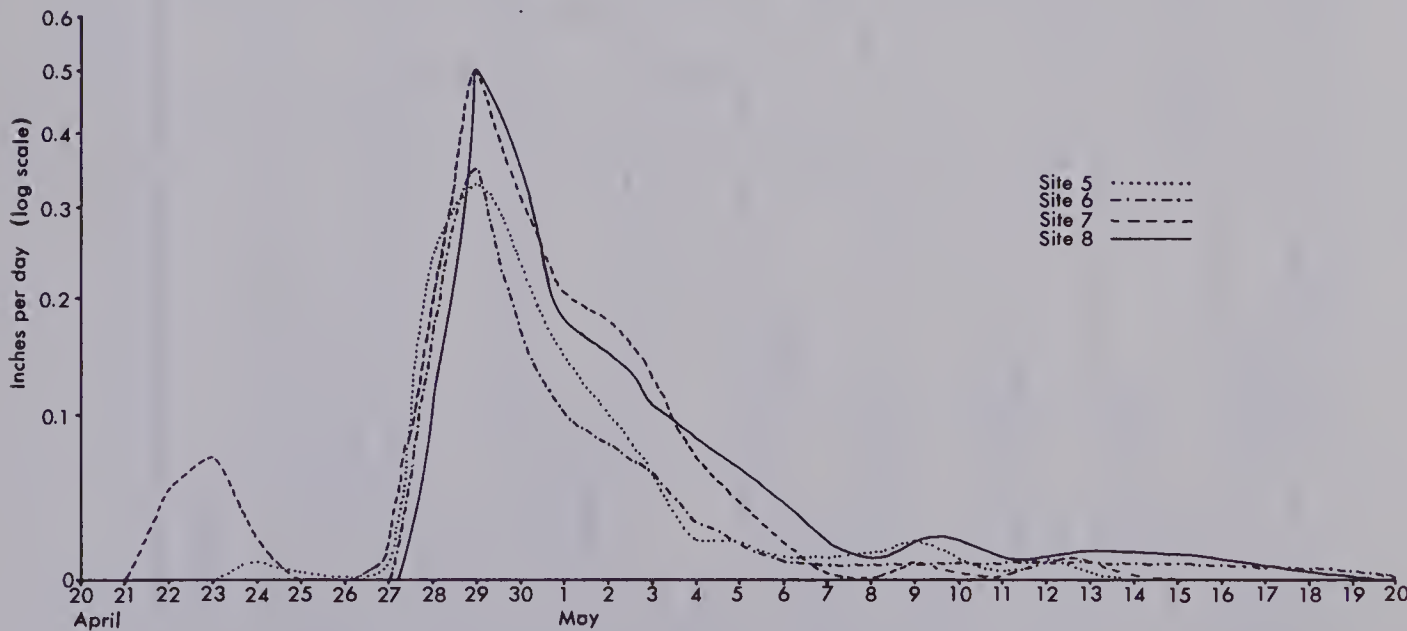
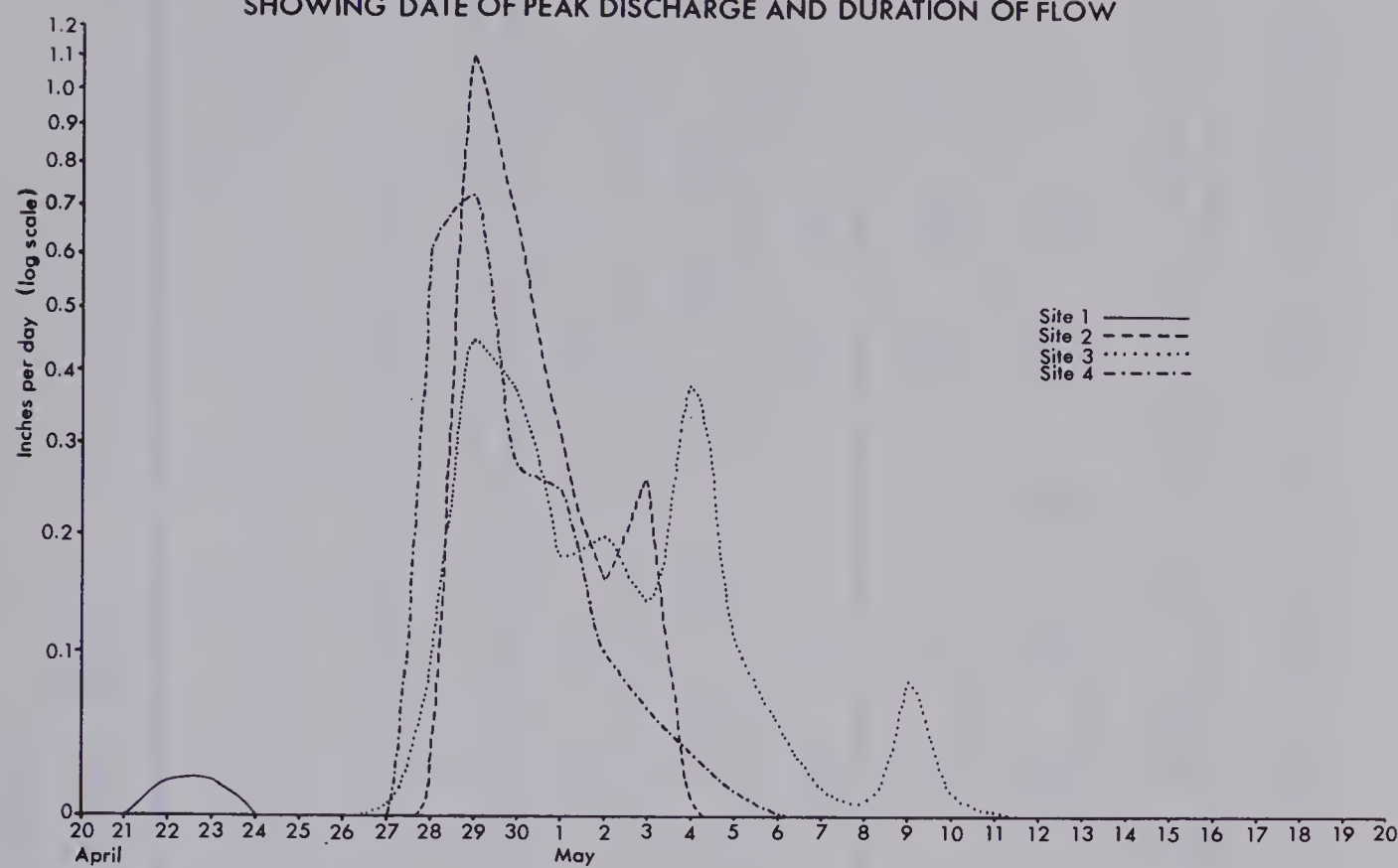


TABLE 1
MELT RUNOFF DATA

Site Number	1	2	3	4	5	6	7	8
Snowpack Water Equivalent (inches)	1.8	3.1	3.1	2.9	3.1	2.4	2.6	3.7
Total Runoff (inches)	0.04	2.55	2.15	2.10	1.14	1.34	1.98	1.86
Runoff (per cent of snowpack)	2	82	69	72	37	56	76	50
Storage (inches)	1.76	0.55	0.95	0.80	1.96	1.06	0.62	1.84
Date of first Flow (April)	22	29	28	27	27	27	22	27
Runoff Duration (Days)	2	6	13	9	24	28	23	28
Date of Peak Flow (April)	23	29	29	29	29	29	29	29
Flow on Peak Day (inches)	0.02	1.11	0.45	0.74	0.35	0.33	0.50	0.50
Percentage of Flow Occurring on Peak Date	50	43.7	21.2	35.5	30.5	24.9	25.5	27.1

inches. There were 3.1 inches of water in the snowpack, thus 69 per cent of the total possible snowmelt was yielded as runoff. This occurred over a period of 13 days from April 28 to May 10. Peak discharge occurred on April 29 with a secondary surge on May 4 (Figure 9). This was the only area with two separate discharge peaks. The dominant flow on April 29 was one of the lowest measured during this study and produced only 0.45 inch of runoff. This discharge was 21.2 per cent of the total volume of flow.

Site 4

Discharge from this south-facing vegetated site was similar to that from the north-facing plot (site 3). A snowpack with a water equivalent of 2.9 inches produced 2.10 inches of runoff. That is, 72 per cent of the snowpack was measured as discharge (Table 1). Flow duration was short, occurring for only nine days from April 28 to May 6. Peak discharge of 0.74 inch of water on April 29 (Figure 9) was considerably higher than for the north-facing site. Runoff on April 29 accounted for 35.5 per cent of the flow from this plot.

Site 5

Runoff from this bare muskeg plot was substantially less than that of the vegetated muskeg (site 6), even though the water content of the snowpack was some-

what greater. This site yielded 1.14 inches of runoff or 37 per cent of the snowpack which had a water equivalent of 3.1 inches (Table 1). Runoff from this area took place over a period of twenty-four days from April 27 to May 20; peak discharge occurred on April 29 (Figure 9). Recorded flow on this date was 0.35 inch and accounted for 30.5 per cent of the total runoff from the plot.

Site 6

The vegetated muskeg produced 1.34 inches of runoff from a snowpack which contained 2.4 inches of water. Discharge from this site was 56 per cent of the available moisture (compared with 37 per cent for the unvegetated muskeg; Table 1). Flow duration from this area was four days longer than from site 5, and occurred on twenty-eight days between April 27 and May 24. April 29 was again the date of peak discharge (Figure 9) and yielded 0.33 inch of water or 24.9 per cent of the total flow from the plot. This was similar to site 5 and was the lowest discharge peak recorded during this investigation.

Site 7

The runoff pattern from this compound bare rock and muskeg area was distinctly different from any of the other sites. Runoff began on April 22 and lasted for twenty-three days until May 14. During this period 76 per

cent of the snowpack was metered as discharge. The water equivalent was 2.6 inches which produced 1.98 inches of runoff (Table 1). Peak discharge occurred on April 29 (Figure 9) and consisted of 0.50 inch of runoff, exactly the same as site 8. This 0.50 inch of water was 25.5 per cent of the total discharge.

Site 8

Runoff from this compound area containing sections of vegetation, muskeg, and bare rock was intermediate between the extremes encountered from the other plots. Fifty per cent of the available moisture was recorded as discharge; i.e., 1.86 inches of flow from a snowpack with a water equivalent of 3.7 inches (the highest snowpack water equivalent in the study area; Table 1). Runoff occurred on twenty-eight days from April 27 to May 24 with a peak discharge occurring on April 29 (Figure 9). Flow on April 29 was 0.50 inch or 27.1 per cent of the total volume.

Daily Runoff Patterns

Daily flow patterns are not as significant an indicator of site variability in snowmelt runoff as are the flow characteristics over the entire runoff period. Daily patterns nevertheless illustrate a number of interesting relationships. The time of peak daily discharge can be related to the amount of incoming solar radiation, which

in turn is dependent upon slope, aspect, vegetation cover, and conditions of the cloud deck. The time of peak flow may also be related to the size of the drainage basin, its surficial material, and its gradient.

Daily runoff showed prominent peaks in each plot early in the snowmelt period, but flow tended to level off as the melt season progressed. All sites (except plot 1) experienced distinct flow peaks on April 29 and 30, and on May 1-3. Diurnal variations for these days are shown in Figure 10. Values for each hour are shown as percentages of the total daily flow. This eliminates the large variability in volume caused by differences in plot size. The time of maximum discharge for these days is averaged for each plot and these averages are compared below (Table 2).

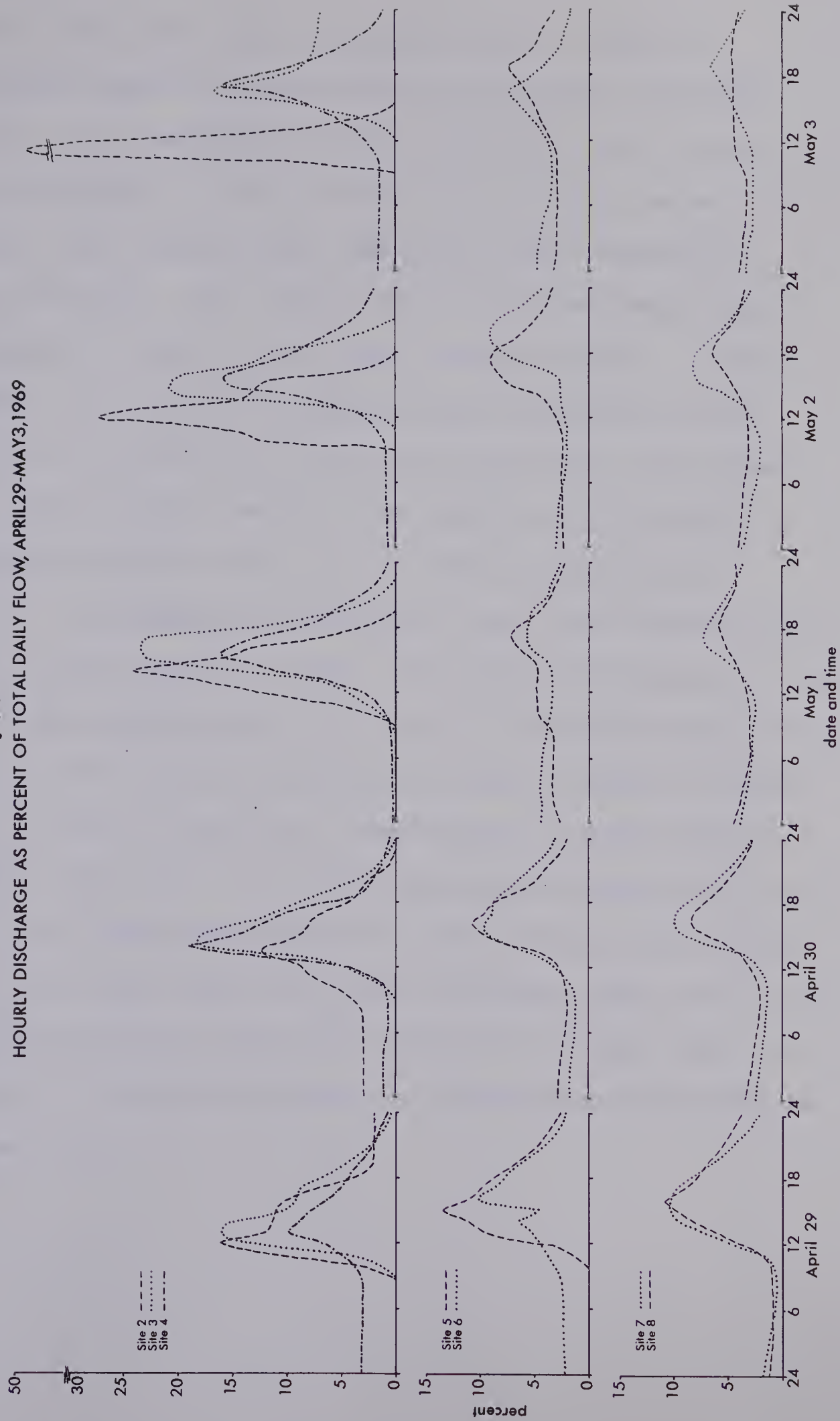
TABLE 2

AVERAGE TIME OF PEAK DISCHARGE APRIL 29 - MAY 3, 1969.

Site	Time
1	no data
2	1230
3	1500
4	1500
5	1645
6	1700
7	1700
8	1730

Examination of Yellowknife hourly temperatures

Figure 10
 HOURLY DISCHARGE AS PERCENT OF TOTAL DAILY FLOW, APRIL 29-MAY 3, 1969



for the five days April 29 through May 3 (Table 3) indicates that air temperatures varied from a minimum of 31°F. to a maximum of 54°F.; since the 31°F. value was registered on only six hours during this period, it is seen that temperatures remained almost constantly above freezing. The time of daily maximum temperature averaged 1530 (M.S.T.) for the five day period. A comparison of the time of maximum daily temperature with the time of peak flow at each plot indicates that sites 2, 3, and 4 peaked earlier than the hour of maximum temperature while sites 5, 6, 7 and 8 peaked later.

As discussed previously, runoff was concentrated early in the snowmelt season. The greatest volume occurred during the period April 28 - May 3. The percentage of the total runoff from the individual sites for each of these days is given in Table 4. Examination of this data indicates that site 3 (the north-facing vegetated plot) produced the lowest percentage of runoff during this period (67.5 per cent) while the total discharge from site 2 (the north-facing bare rock plot) occurred on these days. The reasons for these variations in discharge are examined in Chapter five.

TABLE 3

HOURLY TEMPERATURE (°F.) AT THE YELLOWKNIFE AIRPORT,
April 29 - May 3, 1969

Time M.S.T.	April 29	April 30	May 1	May 2	May 3
1:00	34	36	39	33	39
2:00	35	32	35	33	39
3:00	35	32	35	33	35
4:00	35	32	35	33	35
5:00	31	31	33	33	34
6:00	31	31	33	33	33
7:00	31	31	33	34	35
8:00	37	39	34	36	37
9:00	37	39	34	36	38
10:00	37	39	35	36	41
11:00	44	45	36	45	42
12:00	44	45	36	45	43
13:00	44	45	37	45	46
14:00	48	47	38	51	49
15:00	48	47	38	51	51
16:00	49	47	39	51	54
17:00	49	47	40	50	54
18:00	48	47	40	50	54
19:00	47	47	40	50	54
20:00	47	43	35	46	53
21:00	44	43	35	46	53
22:00	42	43	35	46	48
23:00	36	39	33	39	47
24:00	36	39	33	39	47

TABLE 4

DAILY RUNOFF ON SELECTED DATES SHOWN AS A PERCENTAGE OF
TOTAL 1969 MELT DISCHARGE

Site Number	April 28	April 29	April 30	May 1	May 2	May 3	Total
1	All runoff occurred on April 22 and 23						
2	0	43.7	26.6	12.8	6.6	10.3	99.7
3	4.0	21.2	17.5	8.4	9.5	6.9	67.5
4	29.9	35.5	12.9	12.0	5.1	3.2	98.6
5	15.6	30.5	15.3	8.7	7.2	6.0	83.3
6	17.9	24.9	18.5	11.2	7.9	4.7	75.1
7	10.0	25.5	16.2	10.5	9.4	6.8	78.4
8	6.8	27.1	18.7	10.1	8.3	5.9	76.9

CHAPTER V

FACTORS WHICH CAUSE VARIATION IN SNOWMELT RUNOFF

The previous chapter quantitatively described the patterns of runoff from eight representative sample plots in the study area; the following chapter analyzes the environmental factors which cause variation in snowmelt runoff.

ASPECT

Sites 1 and 2

Wherever snow blankets an area which has topographic expression, aspect becomes an important factor in causing local variation in runoff as the melt season progresses. Four of the eight sample plots exhibited runoff characteristics which are directly attributable to differences in aspect.

Sites 1 and 2, the unvegetated bare rock areas of opposing aspect (north- and south-facing) had a markedly different meltwater regime both in terms of volume of flow and time of peak discharge. The south-facing site (1) contributed almost no runoff (0.04 inch) while the north-facing slope (2) produced the greatest amount of

all the study plots (2.55) inches. The high runoff of site 2 can be attributed to the following factors: the snow cover on this plot averaged 11.5 inches and contained a water equivalency of 3.1 inches. By contrast snow depth on the south-facing plot (site 1) was 7.4 inches and it held an equivalent of 1.8 inches of water. The snow cover of site 2 was north-facing, and thus not subject to as great a sublimation and evaporation* loss as the south-facing plot. Other conditions such as degree of slope, wind direction and intensity, and plant cover are similar for each site, thus radiation-caused differences in sublimation and evaporation (particularly during the period of snowmelt) should account for the variation in amount of runoff.

Snowmelt on south-facing site 1 began on April 22 and patches of bare rock were soon exposed. Water released during the initial stage was insufficient to produce runoff and was retained in the cracks, fractures and plucked depressions of the bedrock. Moisture released from the remaining snowpack spread out over the patches of bare rock where it was held as a thin film by the rough, pitted surface of the granite. Much of this moisture was

* Jeffery (1968) states that direct evaporation loss from the snowpack is small, and accounts for less than three per cent. During snowmelt, however, there may be a substantial water loss through evaporation where water is held as a thin film on low-albedo surfaces.

then lost to evaporation because of the low albedo and subsequent rapid warming of the exposed bedrock. (Such warming would be very slow on a north-facing slope such as site 2 and would result in very little evaporation.)

Although runoff occurred during only two days (April 22 and 23) on site 1, it was not completely devoid of snow until May 2 and water remained in the depressions for several days following this date. During the later stage of snowmelt, some seepage may have occurred through cracks and fractures as the ice which sealed these outlets melted downward.* Such seepage could not have occurred from site 2, the north-facing plot, however.

Sites 3 and 4

These plots also varied significantly in runoff due to aspect. Both sites have similar plant cover, surficial material, and amount of bare rock exposed, but have opposing aspect. Considered over the entire runoff period the two sites produced almost equal flow from similar snow-packs, but the duration of melt was substantially different. Runoff from the south-facing plot (site 4) lasted only nine days, whereas discharge from the north-facing slope (site 3) was measured over a thirteen day period. Although

* The depth to which the freezing isotherm penetrates bedrock at this site is unknown but with only a thin snow cover for insulation, water within fractures probably freezes to a sufficient depth to preclude inferred drainage during the snowmelt period.

peak flow occurred on the same day for both sites, the volume of flow was considerably greater from the south-facing slope (Figure 9). Peak discharge from the south-facing site was 0.74 inch compared with 0.45 inch from the north-facing site (Table 1). This shorter period of runoff and higher flow peak from the south-facing plot can be attributed to the greater input of solar radiation.

Aspect along with vegetation which causes slower melt accounts for the secondary flow peaks from Site 3 (Figure 9). Although total runoff was the second highest of the study plots (2.15 inches, Table 1), flow during the April 28 - May 3 period was the lowest (67.5 per cent, Table 4). This retarded melt left sufficient water in the snowpack to produce secondary flow peaks after the other plots were almost devoid of snow. The effect of aspect on the rate of snowmelt is clearly shown by comparing Plates 24 and 25.

SLOPE

Variations in melt runoff which result directly from slope differences are difficult to isolate. Indirectly, however, slope does cause a number of variations. Steepness of slope is obviously important to drainage. Muskeg areas with their thick accumulations of organic material result from poor drainage which generally reflects a lack of slope. Results of this study confirm

Plates 24 and 25. Both photographs were taken from the same location on the shore of Pocket Lake, on April 29, 1969. Note the more abundant snow cover on the north-facing slope (Plate 24) compared to the completely snow free south-facing slope (Plate 25).



the normal condition that steeper slopes have a lower storage capacity and therefore greater runoff. Seasonal and daily peak discharge tends to be greater from steep slopes and occurs earlier in the day.

Sites 3 and 4 have the steepest slopes of the instrumented plots. The average slope from the upper divide to the basin outlet is 7 degrees for site 3 and 5 degrees for site 4. Sites 5 and 6 on the other hand, have slopes of only 1 degree. The average daily peak discharge for the peak flow period (April 29 - May 3) occurred almost two hours earlier in sites 3 and 4 than at 5 and 6. This difference is probably not solely due to slope - it likely results from the complex interactions of slope with surficial material, length of overland flow, and plant cover.

PLANT COVER

As outlined in Chapter three, vegetation undoubtedly plays an important role in the melting of the snowpack. From data collected in this study, however, it is difficult to relate any significant runoff variations directly to vegetation.

Plant cover is an important indicator of the annual moisture balance of a site. The soil moisture regime of most locations is directly mirrored by the species that colonize it. In turn, the soil water at that local-

ity is dependent upon the nature of the mineral and organic material and this has a greater influence upon melt runoff patterns than does existing vegetation.

The plant cover of plots 5 and 6 (muskeg sites) is important in controlling the amount of moisture storage by its effect on the rate of evaporation and its creation of organic material. (This is amplified in the following section.

STORAGE CAPACITY OF SURFICIAL MATERIAL

Surficial material is the most important physical factor which causes variation in melt runoff in the Yellowknife area. The type of material and its degree of saturation prior to freezup controls the amount of infiltration and storage the following spring.

Bare rock sites are expected to have the lowest storage capacity and to produce the greatest percentage of runoff. This was especially observed in the north-facing bare rock site (2). Storage and evaporation loss at that location was 0.55 inch while 2.55 inches was recorded as runoff. The south-facing bare rock slope (1) did not conform to this pattern and produced very little runoff as discussed in the section on aspect. Although these two patterns are markedly different, that of the north-facing slope appears to be near the norm for bare rock sites in the study area. One-half inch of storage

represents the approximate order of magnitude for areas of exposed bedrock. This agrees with the value suggested by Stene (1967).

Sites covered by thin deposits of coarse, unconsolidated material have a greater storage capacity than areas of bare rock. Data from plots 3 and 4 indicate that available storage in coarse unconsolidated materials on upland ridges is somewhat greater than on exposed rock but it is not as great as was anticipated. Snowmelt contribution to storage in these sites was 0.95 inch and 0.80 inch respectively, while runoff was 2.15 and 2.10 inches (or 69 and 72 per cent of the snowpack moisture content). This small contribution to storage is due to the following factors:

1. Approximately one-quarter of the area of both sites consists of bare rock which has a minimal storage capacity.
2. The coarse, stony material is able to retain only a limited amount of water.
3. Scattered pockets of deeper, fine material with greater moisture-holding capacity were already near saturation at the time of freezup due to heavy rainfall the previous autumn. The small amount of storage that does occur is primarily concentrated in such pockets of finer material and is subsequently diminished by evaporation and trans-

piration from the comparatively dense growth of vegetation which occupies these areas.

The muskeg areas (sites 5 and 6) contain deep accumulations of organic material which permanently store a large volume of water (much of it incorporated in the permafrost). The annual storage capacity however, is not great because of the constantly saturated or near-saturated condition maintained by the peat. Stene (1967) suggests that muskegs in the Yellowknife area have an average annual storage capacity of eight inches; data from the present study do not agree with this figure. If this amount of storage was available for the uptake of melt in the spring, little runoff would occur from such locations. In fact, considerable runoff from muskeg areas was measured during the present study. The absorption of melt water by two muskeg plots was 1.96 inches and 1.06 inches while runoff was 1.14 inches and 1.34 inches respectively. This relatively small contribution is explainable in terms of saturation of the muskeg prior to freezeup the previous autumn (as was the case during the 1968 and 1969 seasons). Precipitation during September 1968 was 2.39 inches, i.e., 1.23 inches greater than the mean. This accounts for the nearly complete recharge of the muskegs as observed during field reconnaissance in October 1968. Further evidence that the muskegs were satur-

ated at the time of the 1968 freezup was provided by soil samples collected the following April.* Analysis of twenty samples, which were collected under the snowcover in muskeg sites, indicates that there was a higher water content in the frozen peat (38 per cent) than in the same samples saturated in the lab (33 per cent). This is probably a result of the growth of segregated ice which forms within the peat as the freezing isotherm penetrates in the autumn (see Corté, 1962). As the frozen active layer thaws during early summer, the supersaturated peat layer gives up part of its moisture content. This does not occur until after the snowmelt period, however, thus any runoff measured during late April and early May is a direct result of snowmelt. This is similar to the findings of Radforth (1963) on Ellesmere Island.

Saturation of these muskegs prior to freezup appears to be a relatively common occurrence and not an anomaly. Examination of precipitation data for Yellowknife indicates a September mean of 1.16 inches and an October mean of 1.10 inches. This relatively high autumn precipitation, coupled with low temperatures and correspondingly low evapotranspiration rates, ensures that organic terrain is at near-saturation at the time of annual freezup.

* Conditions were found to be similar the following autumn (Steiner, 1969, personal communication).

The small difference in storage between the two muskeg sites can be explained by the dissimilarity in plant cover. Site 6 has approximately a ten per cent cover of black spruce and a sixty per cent low shrub cover of labrador tea; the ground itself is covered by cloudberry and sphagnum mosses. Site 5, on the other hand, is completely devoid of live vegetation.* Because of this lack of plant cover, this site can be expected to have a somewhat higher evaporation rate than site 6. This could result in less saturation of the peat during fall and thus a greater capacity for uptake of moisture in the spring.

The effect of shading by a plant cover can normally be expected to exert some control over the depth of the active layer (and thus the available storage volume). In sites 5 and 6, however, this appears to have little effect. A number of active layer depth measurements were made on October 26, 1969 which allow a detailed comparison of the two areas. Thirty-one transect measurements in site 5 and twenty-three similar measurements in site 6 both indicated a mean active layer depth of 2.1 feet (standard deviation 0.6 and 0.9). This indicates that in this particular comparison, a living vegetation cover is not as important in controlling the thickness of the

* Although site 5 lacks a living plant cover, its peat layer is similar to site 6.

active layer as is the insulating layer of organic material.

Site 7 has a number of types of surficial material: approximately half the area is covered by organic soil which averages two feet in depth, one-quarter of the plot is covered by coarse, unconsolidated material, and the remaining quarter is formed by steeply sloping bedrock. Storage in this site was only 0.62 inch, much lower than expected. This low storage can be partially explained by the steeply-sloping granite outcrop which retains substantially less than the one-half inch of storage measured at site 2, another area of bare rock.

The low storage and south-facing aspect of the bare rock quarter of site 7 also account for the early flow on April 22-23. These are the same days that flow occurred from the south-facing bare rock plot (site 7).

The 1.84 inches of storage calculated for site 8 is in the same order of magnitude as that for plots 5 and 6 and can be attributed to the extensive tracts of muskeg in this area.

Previously analyzed peak flow volumes can also be explained in part by the storage differences resulting from inequalities of surficial material. Generally, the areas with low storage capacities tend to have higher peak flows than areas with greater storage. For example, the bare rock site (2) produced 1.11 inches of runoff on the

day of peak discharge while sites 5 and 6 (the muskeg areas) released only 0.35 inch and 0.33 inch respectively. An exception to this pattern was site 3; in this case, the low flow peak can be attributed to the north-facing aspect of the site which delayed snow melting.

SUMMARY AND CONCLUSIONS

Snowmelt runoff patterns were examined during this pilot study in eight contrasting localities within Baker Creek Basin. Preliminary results indicate a surplus of flow from all sample plots, but the volume and timing of discharge varied considerably. Patterns of runoff were found to be dependent upon the complex interaction of a number of physical and climatic factors. Physical components important to melt runoff are extent of exposed bedrock, type and thickness of surficial material, topography, and differences in plant cover. Significant climatic factors are pre-freeze weather events, patterns of winter snow accumulation, and weather conditions during the spring snowmelt season.

The granite bedrock which outcrops in the study area is capable of retaining only a limited amount of water. This is held as a thin film on the surface or in fractures, cracks and plucked depressions. The volume of runoff from any unit area is thus partially dependent upon the areal extent of exposed bedrock. Bedrock is normally not underlain by permafrost, but cracks and fractures are generally sealed by ice during the period of spring melt, thus ground water movement is minimal.

Unconsolidated surface deposits by contrast allow variable amounts of storage. Capacity for moisture uptake

depends upon the type and volume of material. Deposits may be composed of either coarse to fine mineral material, or may consist of organic accumulations made up of litter and peat. The uptake of spring snowmelt by these deposits is significantly governed by pre-freeze weather events and to a minor extent by the limited depth of thaw during the snowmelt season.

Topography influences the rate of spring snowmelt in the following ways: aspect and degree of slope modifies the winter and spring snowpack by causing unequal rates of ablation; relief creates unequal distribution of snow which in turn causes areal variation in the volume of spring melt; topographic differences influence the pattern and density of the plant cover which also affects snow redistribution, to further modify spring snowmelt.

Pre-freeze weather events are very important to snowmelt runoff. The amount of water held in storage by the surficial material at the time of fall freeze-up exerts a strong control over the volume of moisture uptake the following spring.

Duration and intensity of November-March winds greatly affect the patterns of snow accumulation and redistribution; this is responsible for variation in the volume of water held by the snowpack which is reflected during spring melt by areal contrasts in the amount of runoff.

Weather conditions during the spring, particularly the quality of the cloud deck and daily air temperature, directly influence the rate of snowmelt.

Finally, spring runoff patterns are governed by the interaction of all the foregoing physical and climatic functions.

Although these factors exert varying degrees of control over melt runoff, the storage potential afforded by mineral and organic surficial material was found to be the most important. By contrast, the lack of melt retention by large areas of exposed bedrock accentuates the variable nature of water storage within the heterogeneous environments of the Canadian Shield. In general, sites with low storage capacities, such as areas of bare rock, were found to produce the largest volume of runoff. Areas with large storage capacities, such as the organic accumulations of the muskeg tracts, produced the smallest volume of flow. The amount of discharge was considerable from these areas, however, and was much greater than anticipated. The storage capacity of muskeg is normally expected to be capable of retaining much of the snowmelt, thus resulting in little or no runoff. As suggested by the preliminary results of this study, however, this was not the case. Rainfall in the pre-freeze periods of 1967-1969 resulted in almost complete saturation of the muskegs, with the consequence that snowmelt surpluses in excess of one inch were recorded as runoff. Pre-freeze climatic events were thus found to be the second major factor in controlling snowmelt runoff in the Yellowknife area.

In conclusion, this preliminary study presented a number of research topics which if pursued might aid a more

complete understanding of the water balance in a Subarctic environment:

1. Contrasting rock types and their characteristic weathering and erosion patterns produce differences in runoff. Such flow variations may be of considerable hydrologic significance in the heterogeneous lithologic environment of the Canadian Shield.
2. The active layer of permafrost is capable of storing large volumes of water. The significance of this seasonally thawed layer (especially in muskeg sites) to the annual water balance of the Baker Creek Basin is especially in need of further study.
3. Evaporation of snowmelt from low-albedo south-facing rock surfaces was found to be significant in this study. During years in which the melt season is extended, evaporation in this manner could result in considerable water-loss and correspondingly reduced runoff.
4. Pre-freeze saturation of muskeg during the study period was suggested as the major factor causing significant melt runoff. A comparative examination of spring flow from areas of organic terrain following a dry autumn is desirable for a more complete understanding of melt runoff in Baker Creek Basin.
5. As mentioned previously, large accumulations of ice

("naled") build up along much of Baker Creek Valley during the winter months. The effects of icing upon the water balance, channel geomorphology, and distribution of ecosystems along Baker Creek are worthy of additional research.

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